DEVELOPMENT OF THE FIVE DEGREE-OF-FREEDOM LINEAR MODEL FOR THE XR-3 SURFACE EFFECT SHIP AND INVESTIGATION OF THE ROLL BEHAVIOR OF THE CRAFT IN TURN MANEUVERS

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by

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I. INTRODUCTION

A. BACKGROUND

The Surface Effect hybrid type high performance ship has been of great interest recently, and in 1970 the XR-3 test craft was delivered to the Naval Postgraduate School. As seen in [7] Leo and Boncal converted the digital simulation program for the 100-B test craft to represent the XR-3, thus providing a nonlinear model. In [1], Gerba and Thaler have developed a heave-only linear model and further studies were made by Barnes in [2] by developing a two degree-of-freedom linear pitch and heave model representing the XR-3 test craft.

B. OBJECTIVE

In order to investigate the roll behavior of the XR-3 test craft during turn maneuvers, a five degree-of-freedom linear model is developed in this thesis. Some modifications are made for pitch and heave modes, therefore test of the vertical plane by means of weight removal is reinvestigated and compared with the nonlinear simulation results.

In [3], the roll behavior of the XR-3 and the sidewall sensitivity are studied using a six degree-of-freedom non-linear model. Similar studies are made in this thesis after developing a five degree-of-freedom linear model and comparing with the nonlinear model results. Finally, some modifications are suggested for nonlinear modeling.

II. NONLINEAR XR-3 MODELING FOR FIVE DEGREE-OF-FREEDOM

A. ASSUMPTIONS

The following assumptions and simplifications are used during development of a constant speed XR-3 test craft model:

1. Aerodynamic drag on the forward seal, and superstructure skin friction forces are neglected.

2. Momentum (ram) drag is disregarded for all modes. In other words, it is accepted that the location of the lift fans with respect to the craft C.G. could not affect significantly the roll and pitch stability. Also, air stagnation force in the z-direction is assumed to be negligible.

3. During dynamic response of the craft, only air leakage with constant leakage area at the stern seal is assumed. No other air escape is considered such as possible leakage from sidewalls or bow seal.

4. Plenum pressure and air mass thermodynamics are represented by ideal diabatic processes with the air constant specific heat ratio $\gamma = 1.4$.

5. Effective plenum roof area is developed as a function of craft weight.

6. Planing forces are concentrated at the centroid of the keel longitudinal cross section through the fluid medium.

7. Pitch and roll damping moments due to added mass are included in the craft dynamics, but their contribution to heave motion is neglected.

8. The thrust forces and all hydrodynamic resistive forces (drag) in the z-direction cancel each other, since at constant speed operation, these forces are in equilibrium. However they might contribute to the moment equations such as pitch moment, but considering their effective moment arms with respect to the C.G. are almost equal to the thrust moment arm, so that their contribution in the moment equations is also neglected.

9. For seal modeling, vertical resistive forces due to hydrodynamic response are taken into account including corresponding effective wetted seal area.

10. Simplified craft geometry is used for plenum, buoyancy and seal modeling.

B. COORDINATE SYSTEM AND SIGN CONVENTIONS

1. The cartesian coordinate system is used with its origin located on the water line corresponding to the craft center of gravity.

2. The x-axis lies on the water line with the positive longitudinal displacement being measured forward.

3. The y-axis lies in the vertical cross section plane with the lateral dislacement being measured positive to starboard.

4. The z-axis lies in the vertical cross section plane with the positive vertical displacement being measured downward.

5. z represents heave C.G. displacement measured from the origin (at water line) to the center of gravity.

6. z_s is one of the craft dimensional values measured from the keel to the C.G.

7. Pitch is the rotational motion about the y-axis, angular pitch displacement is represented by θ, positive pitch angle is measured upward (boat noses up).

8. Roll is the rotational motion about the x-axis, ϕ angle represents angular roll displacement, positive roll angle is measured to starboard (boat heels to starboard).

9. Similarly the yaw is the rotational motion about the z-axis, positive yaw is measured in the clockwise direction.

10. Positive roll, pitch and yaw moments are to be defined as the moments in the positive roll, pitch and yaw directions correspondingly.

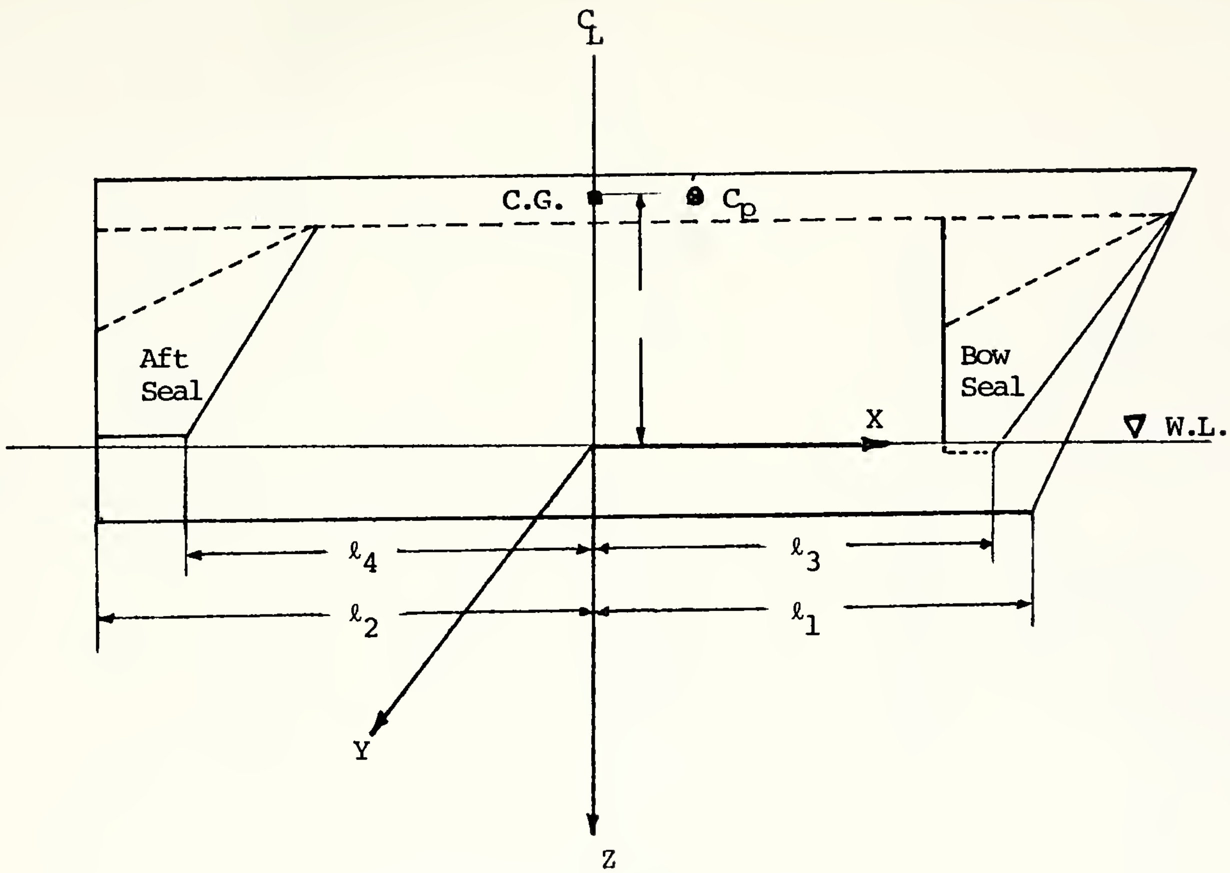
11. As a reference zero pitch and roll angle provide the x-y plane parallel to the water surface.

The craft coordinate system is shown in figure 1.

C. SIMPLIFIED CRAFT MODELING AND GEOMETRY

1. General Simplified Geometry and Dimensions of the XR-3 Test Craft

In figure 1 the sideview simplified geometry of the XR-3 test craft is shown. Also in figure 3 the top view is illustrated. The variables and dimensions in these figures are defined as follows;



SIDEVIEW

Figure 1. Craft coordinate system and simplified geometry (sideview)

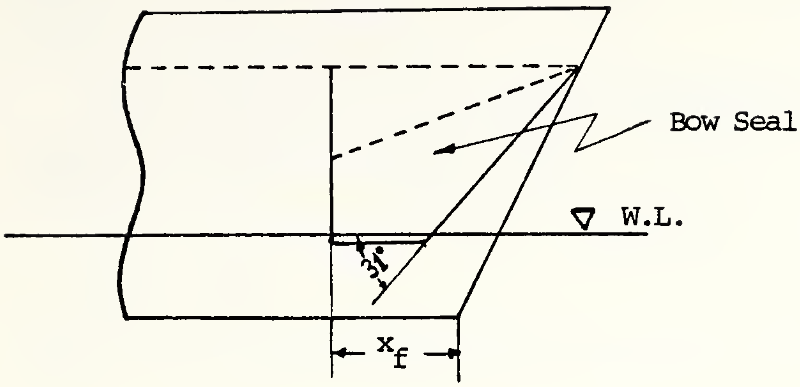


Figure 2. Bow seal geometry

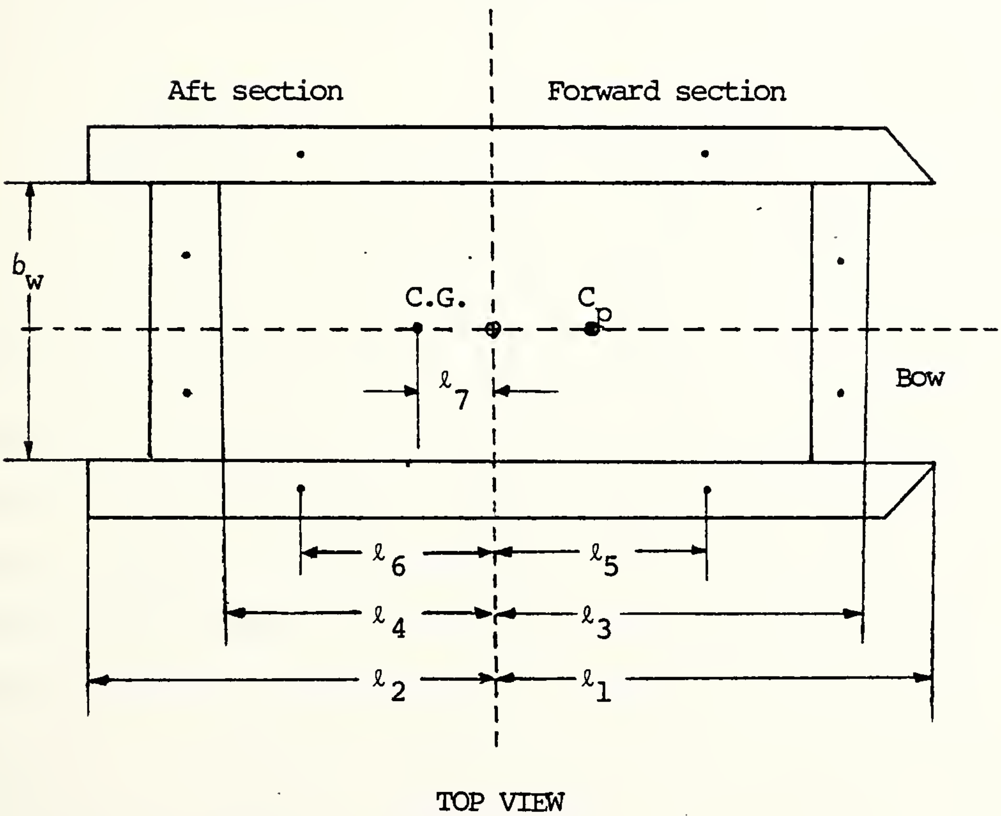


Figure 3. Simplified geometry (top view)

ℓ_d = Draft of the craft at center of gravity

C_p = Plenum pressure center (the centroid of the effective plenum area)

ℓ_5, ℓ_6 = The longitudinal distance of the sections' centroids from the C.G. (forward and aft section centroids respectively)

ℓ_3, ℓ_4 = Bow and stern seals front face distances at water level

ℓ_7 = Centroid distance of the planing force effective area

ℓ_1, ℓ_2 = Forward and aft sections sidewall submerged region length.

All craft dimensional values are taken from the XR-3 six degree-of-freedom model scale drawings as indicated in [2] and [3].

2. Sidewalls

As reported in [2], the sidewall modeling is developed from the SIDEWALL subroutine of the 6 DOF computer model. Like craft dimensions, all sidewall dimensions and their related geometric configurations are based on scale model drawings. For simplicity of calculation, the sidewalls are divided into two sections called forward and aft. During dynamic response of the sidewalls, these sections are considered individually with their own centroids, so related calculations can be done easily. Especially, the sidewall modeling is developed in order to determine buoyancy forces and moments. By means of this modeling, the average sidewall width, average draft at section centroid and effective

plenum area are also determined and used extensively in the rest of the calculations.

The sidewall vertical cross sections at the section centroid forward and aft are sketched in figures 4(a) and 4(b) respectively. From these figures, the average forward sidewall width at the buoyancy center is found to be

$$\bar{b}_f = \frac{\ell_f}{2 \tan \beta_1} + b_f \qquad \text{(II-1)}$$

where

ℓ_f = Draft at forward buoyancy center

$\tan \beta_1$ = Tangent of the sidewall deadrise angle at the forward buoyancy center

b_f = Sidewall flat surface width at the kell (forward section)

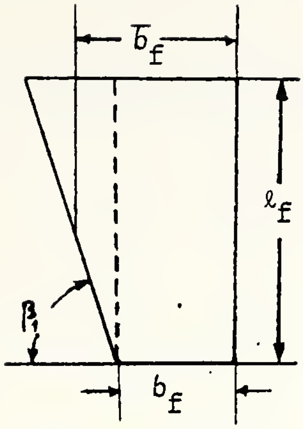
Therefore submerged sidewall volume of the forward section is given as follows

$$V_1 = \bar{b}_f \, \ell_f \, \ell_1 \qquad \text{(II-2)}$$

ℓ_f can be formulated as

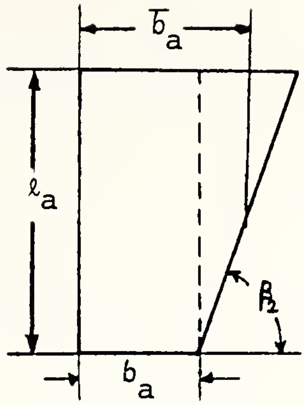
$$\ell_f = \ell_d - \ell_5 \tan \theta$$

then the small angle approximation $\tan \theta \doteq \theta$ gives



Forward section

Figure 4(a)



Aft section

Figure 4(b)

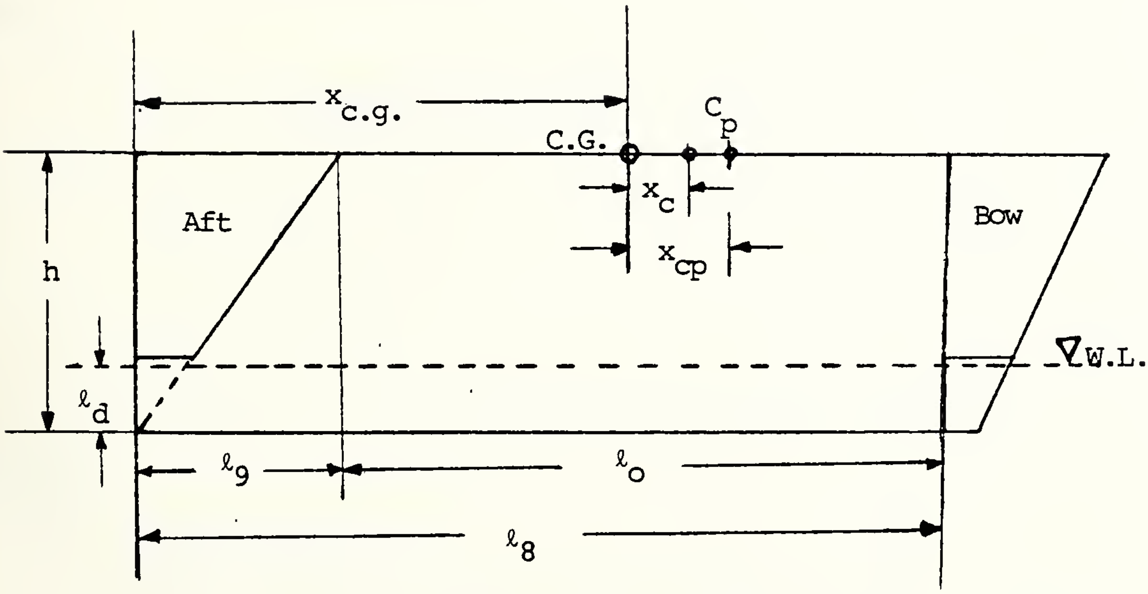


Figure 5. Plenum modeling

$$\ell_f = \ell_d - \ell_5 \theta \qquad \text{(II-3)}$$

As defined before, ℓ_d draft at C.G. is

$$\ell_d = z_s + z \qquad \text{(II-4)}$$

Similar expressions can be derived for the aft section,

$$\bar{b}_a = \frac{\ell_a}{2 \tan \beta_2} + b_a \qquad \text{(II-5)}$$

where

b_a = sidewall flat surface width at the keel (aft section)

$$V_2 = \bar{b}_a \ell_2 \ell_a \qquad \text{(II-6)}$$

$$\ell_a = \ell_d + \ell_6 \theta$$

Note that ℓ_f, ℓ_a are functions of draft and pitch angle.

3. Plenum Modeling

In [2] plenum modeling is presented including plenum pressure variation due to changing of draft. In the development of a pitch, heave and roll linear model, the simplified plenum geometry and dynamics which were derived by Barnes are considered and used in our plenum dynamics representation.

The variables and dimensions for plenum modeling, as seen in figure 5, are found as

$$\ell_p = \ell_8 - \ell_9 \left(\frac{\ell_d}{h}\right) \tag{II-8}$$

$$A_b = b_w \ell_p \tag{II-9}$$

$$\ell_9 = \ell_8 - \ell_o$$

where

ℓ_p = Length of plenum at the water line

A_b = Effective plenum area

b_w = Lateral distance from one sidewall to another in the plenum region.

ℓ_9, ℓ_8, ℓ_d, ℓ_o and h are all constants related to craft dimensions. Only the effective plenum area A_b varies when the craft draft varies, that means variation of the plenum pressure centroid C_p is forward or backward.

4. Bow and Aft Seals

The seals are an involved additional dynamic system with their own degree of freedom relative to the craft, and they carry little load compared with the other components of the craft. However in the simplified model, the seal motions relative to the craft are neglected.

The assumed seal geometry is shown in figure 2, developed in [2]. Using an appropriate geometric configuration, the seal wetted area is derived as a function of craft draft and pitch angle.

From [2], the width of the wetted surface for the bow seal is;

$$x_f = \frac{\ell_d - \ell_3 \tan\theta}{\sin 31°} \tag{II-10}$$

where

$\sin 31°$ = sin of the angle between water surface and the bow seal front face.

The numerator of this ratio represents draft at the bow seal front face.

A similar expression for the stern seal is;

$$x_a = \frac{\ell_d + \ell_4 \tan\theta}{\sin 32°}$$

Multiplying x_f and x_a by b_w, bow and stern seals wetted areas are obtained as follows;

$$A_f = b_w x_f$$

$$A_a = b_w x_a$$

5. <u>Rudder and Propulsion Hydrodynamics</u>

The rudder hydrodynamics is calculated from [4], inserting rudder geometry dimensional values into the fin equations. Actually we are interested in the lateral force (sway) on the rudders for a given rudder order deflection. This dynamic equation is given in [4] as follows;

$$Y_r = \rho u^2 A_r (1 + \frac{d_s}{h_r}) C_r [\delta_r - (1 + \frac{d_s}{h_r}) \frac{V_h}{u}] \qquad \text{(II-11(a))}$$

where

A_r = Rudder platform area (for one rudder only)

d_s = draft at the stern = $z + z_s - x_r \theta$

h_r = Vertical depth to bottom tip of the rudder

C_r = Rudder lift coefficient

$= \frac{2\pi R_a}{R_a + 3}$ (for fully wetted flow regime)

R_a = The rudder aspect ratio

δ_r = Rudder deflection (the sign convention of the rudder is to be positive for port turn)

V_h = $V + x_r r - z_s p$

x_r = longitudinal coordinate of rudder geometric center (always negative value)

V = lateral speed (ft/sec)

r = yaw rate (rad/sec)

In order to simplify the rudder dynamic equation, the following coefficients are defined as

$$C_e = 1 + \frac{d_s}{h_r}$$

$$C_t = \rho u^2 A_r (1 + \frac{d_s}{h_r}) C_r$$

Then equation (II-11(a)) becomes

$$Y_r = C_t(\delta_r - C_e \frac{V_h}{u}) \quad \text{(II-11(b))}$$

Let us define z_r to be the vertical coordinate of the rudder from the C.G. to its geometric center, the rudder roll and yaw moments can be calculated from

$$K_r = - Y_r z_r \quad \text{(II-11(c))}$$

$$N_r = Y_r x_r \quad \text{(II-11(d))}$$

During turn maneuvers, the propulsion thrust vector is also deflected according to the given rudder order. Therefore the lateral component of the thrust contributes yaw and roll moments as well as a sway mode, but this diturbance must be considered as a step input to the linear modes with constant magnitude, therefore the total propulsion sway force is

$$Y_{pr} = 2 X_t \sin \delta_r \quad \text{(II-12)}$$

where X_t is the propulsion thrust corresponding to craft speed.

Similarly the roll and yaw moments generated by the propulsion system are

$$K_{pr} = Y_{pr} z_p \quad \text{(II-13(a))}$$

$$N_{pr} = Y_{pr} x_p \qquad (II-13(b))$$

where x_p and z_p are the longitudinal and vertical locations of the propeller respectively.

D. DYNAMIC FORCES FOR FIVE DEGREE-OF-FREEDOM MODES

1. Seal Forces

Considering the seal configuration and dynamics, the pressure difference across the wetted portion of the seal is

$$\bar{P}_b = P_b - P_a$$

where

$\bar{P}_b$ = Plenum gauge pressure (lb/ft^2)

P_a = Atmospheric pressure

Since the seal is in equilibrium, the vertical hydrodynamic force on the seal is

$$Z_{sf} = -\bar{P}_b A_f$$
$$= -\bar{P}_b \cdot b_w\left(\frac{\ell_d - \ell_3\theta}{\sin 31°}\right) \qquad (II-14)$$

For the stern seal hydrodynamics, a similar expression can be found as

$$Z_{sa} = -(\bar{P}_b + P_i)\cdot \ell_d\left(\frac{\ell_d + \ell_4\theta}{\sin 32°}\right) \qquad (II-15)$$

where

P_i = Additional pressure supplied into stern air bags in order to reduce leakage.

2. Buoyant Forces

The forward section buoyant force is determined from equation (II-2), it is

$$Z_{bf} = -2 \rho g V_1$$

here ρ is the density of the seawater and g is the gravitational constant.

Finally, the forward and aft section forces are

$$Z_{bf} = -2 \rho g \left(\frac{\ell_f}{2 \tan \beta_1} + b_f\right) \ell_f \ell_1 \qquad \text{(II-16)}$$

$$Z_{ba} = -2 \rho g \left(\frac{\ell_a}{2 \tan \beta_2} + b_a\right) \ell_a \ell_2 \qquad \text{(II-17)}$$

3. Planing Forces

In addition to the pitch angle θ, the sidewall flat area at the keel determines the planing effect of the craft. When the craft pitches up, the frontal area (through the fluid medium) causes a lift-drag force in the z-direction.

The planing force, from Reidel's work [3], is;

$$Z_{p\ell} = -\frac{1}{2} \pi \rho A u^2 \sin \theta$$

where

A = flat surface area at the keel

u = speed of the craft

Using the small angle approximation and including the loss coefficient C_{pl} suggested by Barnes in [2], the planing force is redetermined as

$$Z_{pl} = - C_{pl} \pi \rho A u^2 \theta \qquad \text{(II-18)}$$

A similar expression is derived for sidewall dynamics in [4], but in our modelling equation (II-18) is used.

4. Pitch Damping Forces

The sidewalls of the surface effect ship influence moderately heave, pitch and roll modes, so in [4] the hydrodynamic and hydrostatic forces and moments acting on the sidewalls of uniform triangular cross section are derived with particular application to vertical plane motion and lateral motion.

Considering constant speed operation of the craft, neglecting some terms in the equations provided from [4], the vertical force acting on only one sidewall is found as;

$$Z_{sw_1} = A_{33} x_s u q \qquad \text{(II-19)}$$

where

A_{33} = vertical added mass calculated at the stern

= $(\pi/8)\ \rho\ B_s^{\ 2}$

B_s = value of sidewall waterline at the sidewall stern

x_s = stern distance from C.G. (negative value)

q = pitch rate (rad/sec).

For the pitch damping moment, the same equation is used by Barnes in [2].

5. <u>Roll Damping Forces</u>

The XR-3 test craft is dynamically similar to 100-B surface effect ship. Therefore we can use dynamic equations calculated in [4] for the XR-3 test craft. The heave-roll damping force for one sidewall can be written as;

$$Z_{sw_2} = - A_{33}\ u\ b_o\ p \qquad \text{(II-20)}$$

In the above equation, b_o is half of the craft width and it must be used (+) for starboard sidewall, (-) for port sidewall.

Similarly the lateral damping force due to sidewall hydrodynamics is

$$Y_{sw_1} = - A_{22}\ u(v + x_s r - z_s p) \qquad \text{(II-21)}$$

here A_{22} is the lateral added mass calculated at the stern, p is the roll rate. A_{22} is calculated from [4], that is

$$A_{22} = \pi/5\ \rho\ d_s^{\ 2}$$

6. <u>Plenum Pressure Lift Force</u>

From [2] and [4], the plenum pressure lift force is determined assuming uniform pressure distribution, This is formulated as

$$Z_p = -A_b\ \overline{P}_b$$

from equations (II-8) and (II-9) follow

$$Z_p = -b_w\ \overline{P}_b(\ell_8 - \frac{\ell_g\ \ell_d}{h}) \qquad \text{(II-22)}$$

E. DYNAMIC PLENUM AIR MASS, PRESSURE EQUATIONS

Assuming constant aft seal leakage area, the leakage flow rate (Q_{out}) is given by Gerba and Thaler for the XR-3 heave only model in [1], then we have

$$Q_{out} = C_n\ A_\ell (\frac{2\ \overline{P}_b}{\rho_a})^{1/2} \qquad \text{(II-24)}$$

where

C_n = Nozzle flow coefficicnet

A_ℓ = Leakage area

ρ_a = Atmospheric air density.

The linearized air flow (Q_{in}) into the plenum is presented in [5] according to the fan properties and calculated in [1] as follows,

$$Q_{in} = n(Q_o - k_p \bar{P}_b) \qquad \text{(II-24)}$$

where n is the number of fans supplying the air to the plenum, Q_o is the steady state air flow rate corresponding to steady gauge pressure, k_p is (1/slope) of the $\bar{P}_b$ vs. Q_{in} curve at the equilibrium point.

From equations (II-23) and (II-24), the plenum air flow rate can be written as

$$\dot{M}_b = \frac{dm_b}{dt} = \rho_a(Q_{in} - Q_{out}) \qquad \text{(II-25)}$$

The equation (II-25) reveals thatif the fan flow rate (Q_{in}) equals to the leakage flow rate (Q_{out}), then the plenum air mass (M_b) is constant.

The absolute plenum pressure is calculated from

$$P_b = P_a\left(\frac{M_b}{V_b\ \rho_a}\right)^{\gamma} \qquad \text{(II-26)}$$

In the above equation, V_b is defined as plenum volume and its simplified form is calculated from [1],

$$V_b = (V_n - A_b \ell_d) \qquad \text{(II-27)}$$

where V_n is to be the empty plenum volume.

F. NET HEAVE FORCE

The resultant heave force is the summation of the all external dynamic forces, it is

$$Z = Z_{sf} + Z_{sa} + Z_{bf} + Z_{ba} + Z_{pl} + Z_{sw} + Z_p$$

where

$$Z_{sw} = Z_{sw_1} + Z_{sw_2}$$

Z_{sw} also includes a pair of heave buoyancy forces due to roll, but they are in opposite directions. Therefore these stabilizing forces are only taken into account in the roll motion.

G. PITCH AND ROLL MOMENTS

1. Seal Moments

a. Pitch Mode

The seal force is modeled by Barnes in [2] acting on the center of the seal wetted length. The effective pitch moment arms are;

$$\ell_{sf} = \ell_3 - x_f/2 \quad \text{(for forward seal)} \qquad \text{(II-28)}$$

$$\ell_{sa} = \ell_4 + x_a/2 \quad \text{(for aft seal)} \qquad \text{(II-29)}$$

From this follows the forward and aft seal moments

$$M_{sf} = - Z_{sf} \ell_{sf} \tag{II-30}$$

$$M_{sa} = - Z_{sa} \ell_{sa} \tag{II-31}$$

where Z_{sf} and Z_{sa} have already been defined.

b. Roll Mode

The flexible seals can contribute little to roll stability. Actually the seal configurations and hydrodynamics are relatively more complex. In [4], the seal roll moments are calculated by combining the roll contribution of all seal elements.

Considering the seal response, the submerged region of the seal can be calculated and its roll moment contribution can be formulated in the following equations;

$$K_{sf} = - b_w^3/12 \; \rho \; g \; x_f \tan \phi \tag{II-30}$$

$$K_{sa} = - b_w^3/12 \; \rho \; g \; x_a \tan \phi \tag{II-31}$$

For this modeling, the roll moment arm is considered as $(2/3 \; b_o)$, that is the centroid of the triangle cross section of the submerged portion.

2. Buoyant Moments

a. Pitch Mode

The pitch buoyancy moments are calculated from equation (II-16) and (II-17) assuming constant moment arms

ℓ_5 and ℓ_6. The pitch buoyancy moments are

$$M_{bf} = - Z_{bf} \ell_5 \tag{II-32}$$

$$M_{ba} = Z_{ba} \ell_5 \tag{II-33}$$

b. Roll Mode

As discussed in the heave mode, the effect of the sidewall buoyancy due to the roll is to be a stabilizing moment. From figures 4(a) and 4(b) the buoyancy volume change can be approximated as

$$\Delta V_f = \left(\frac{b_f + b_w}{2} + \frac{\ell_f}{2 \tan \beta_1}\right)\left(\frac{\ell_f}{\tan \beta_1} + b_f\right) \ell_1 \phi \tag{II-34}$$

Finally, roll moment is

$$K_{bf} = - 2 \rho g \Delta V_f \tag{II-35}$$

Similarly, the aft section roll moment is

$$K_{ba} = - 2 \rho g \Delta V_a$$

3. <u>Planing Pitch Moment</u>

The planing effect due to the sidewall flat area at the keel contributes only pitch motion as follows;

$$M_{pl} = Z_{pl} \ell_7$$

4. Pitch Damping Moment

This is calculated from equation (II-19) as

$$M_{sw} = - 2 Z_{sw_1} x_s = - 2 A_{33} u x_s^2$$

In the above equation, the factor "2" appears because there are two sidewall sections.

5. Roll Damping Moment

Combining equation (II-20) and (II-21), the roll damping component is

$$K_{sw} = 2 Z_{sw_2} b_o - Y_{sw_1} z_s + K_{wave} \qquad \text{(II-37)}$$

where K_{wave} represents the additional roll damping term because of vertical wave generation in the roll.

From [3] and [4], K_{wave} is

$$K_{wave} = - 32/\pi \; b_o^2 \; B_c \; P \qquad \text{(II-38)}$$

Here, B_c is the sidewall vertical added mass given as

$$B_c = \pi/8 \; \rho \; \ell \; \ell_d^2 \; \text{Cotan}^2 \beta \; .$$

6. Plenum Pitch Moment

From equation (II-22) and defining X_{cp} to be the plenum pressure centroid, the plenum pitch moment is given as

$$M_p = -Z_p X_{cp} = A_b(P_b - P_a) X_{cp}$$

where X_{cp} is calculated as a function of craft draft in [2] as follows;

$$X_{cp} = X_c + (\ell_g \ \ell_d)/2h$$

$$X_c = \ell_8/2 + X_{c.g.}$$

7. Plenum Roll Moment

The destabilizing static plenum roll moment is generated when the craft rolls to one side. Since the effective plenum pressure centroid shifts laterally to the other side tending to increase rolling of the craft. The plenum roll moment is

$$K_p = A_b(P_b - P_a)(z_s - \ell_d)\phi$$

8. Rudder and Propulsion Roll Moments

These roll moments have already been calculated from equation (II-11(c)) and (II-13(a)).

H. SWAY FORCES

1. Cross Flow Drag (Sidewall)

During the turn maneuver, the cross flow drag is generated acting on the outboard sidewall. The direction of this force is negative while turning to the left.

Neglecting the lateral drag component inside of the sidewall, the net cross flow drag can be calculated from

$$D_{sw} = -\frac{1}{2}\rho \operatorname{sign}(V_r)\, C_d\, V_r^2\, \ell(\ell_d \pm b_o\phi) \qquad \text{(II-39)}$$

where

$$V_r = v + x_s r - (z_s - \ell_d/2)p$$

$$C_d = \text{cross flow drag coefficient}$$

Considering the outboard surface of the submerged sidewall sections (dead rise angle effect),the lift force in the z-direction can be produced due to the lateral drag deadrise projection. In [4], the importance of the sidewall deadrise angle is mentioned, however at the hydrodynamic section in this reference, the lift component of the drag force has not been derived.

In this modeling, the lift force (Z_d) and lateral drag component is calculated assuming both have the same drag coefficients (C_d = 1.28). They are

$$Y_d = D_{sw} \sin\beta \qquad \text{(II-40)}$$

$$Z_d = D_{sw} \cos\beta \qquad \text{(II-41)}$$

From equation (II-40) and (II-21), the total hydrodynamic sway force of the sidewall is

$$Y_{sw} = (D_{sw} + Y_{sw_1}) \sin \beta + Y_{sw_1} \qquad \text{(II-42)}$$

2. <u>Centrifugal Force</u>

The centrifugal force acting on the C.G. of the craft is always in the outboard direction during the turn maneuver. Y_c is the centrifugal force, given as

$$Y_c = - m \frac{u^2}{R}$$

R, the turning radius is equal to (u/r), combining this with the above equation gives

$$Y_c = - m\ u\ r \qquad \text{(II-43)}$$

a negative sign is used due to the coordinate system sign convention. Since the right turn produces (+) yaw rate, then Y_c is calculated as (-), so outboard sway force is generated for this configuration.

3. <u>Rudder and Propulsion Sway Forces</u>

They are determined from equation (II-11(b)) and (II-12).

The sway forces due to the seals, air plenum and aerodynamic drag are neglected in this modeling.

I. YAW MOMENTS

1. Sidewall Yaw Moment

The sidewall yaw dynamic equations are given in [4]. After some simplification, the net widewall yaw moment is calculated from

$$N_{sw} = N_1 + N_2 + (X_{pw} - X_{sw})\ b_o \qquad \text{(II-44(a))}$$

where

$$N_1 = 2u(v + x_s r - z_s p)A_{22}\ell(1 - \lambda)$$

$$- \pi/5 \cdot \rho(\ell_d \pm b_o\phi)^2 \ell u(v - z_s p) \qquad \text{(II-44(b))}$$

$$N_2 = - \rho\ C_d\ \ell_d(2\ s_1\ \ell^3\ r\ V + s_2\ \ell^2\ V_r^{\ 2}) \qquad \text{(II-44(c))}$$

$$\lambda = \frac{\ell + X_s}{\ell} \qquad \text{(II-44(d))}$$

= The ratio of C.G. location of sidewall bow to the craft length

$$s_1 = \frac{1 - 3\lambda(1 - \lambda)}{3} \qquad \text{(II-44(e))}$$

$$s_2 = \frac{2\lambda - 1}{2} \qquad \text{(II-44(f))}$$

$$X_{pw} = - 1/2\ \rho\ C_f\ A_{w_p}\ u^2 \qquad \text{(II-44(g))}$$

= port wetted area surge resistive force

$$X_{sw} = - 1/2\ \rho\ C_f\ A_{w_s}\ u^2 \qquad \text{(II-44(h))}$$

= starbord wetted area surge resistive force

$$A_w = [2(\ell_d \pm b_o\phi) + b_s]\ell \qquad \text{(II-45)}$$

$$b_s = \frac{b_f + b_d}{2}$$

= Average sidewall flat surface width at the keel.

In equation (II-45) ± term related to the starboard or port wetted surface calculations.

2. Rudder and Propulsion Yaw Moments

The yaw moments due to the rudder and propulsion system are determined from equation (II-11(d)) and (II-13(b)) respectively.

The seals, air plenum and aerodynamic yaw moments are neglected. Actually the aerodynamic yaw moment should be taken into account. Since during the turn maneuver, the yaw drift angle is produced, thus a positive aerodynamic yaw moment contribution to the yaw motion has been generated. From 6 DOF nonlinear model simulations, this contribution is determined at 5.2% of the total yaw moment.

J. TOTAL PITCH MOMENT

The summation of the all dynamic pitch moments gives the net pitch moment which can be written as

$$M = M_{sf} + M_{sa} + M_{bf} + M_{ba} + M_{pl} + M_{sw} + M_p \qquad \text{(II-46)}$$

K. TOTAL ROLL MOMENT

Before calculating net roll moment, the roll moment equation due to the cross flow drag term must be derived. Including also the added mass effect to the equation (II-40) and (II-41), the result is

$$K_d = (D_{sw} + Y_{sw_1})(b_o \cos\beta - z_o \sin\beta) \qquad \text{(II-47)}$$

Combining all roll dynamic equations, the net roll moment is calculated as

$$K = K_{sf} + K_{sa} + K_{bf} + K_{ba} + K_{sw} + K_{pr} + K_r + K_p + K_d$$

L. TOTAL SWAY FORCE

From equation (II-11(a)), (II-12), (II-42) and (II-43), the total sway force is obtained as

$$Y = Y_r + Y_{pr} + Y_{sw} + Y_c \qquad \text{(II-48)}$$

M. TOTAL YAW MOMENT

The summation of the sidewall, rudder and propulsion yaw moments gives the net turning moment about the z-axis

$$N = N_{sw} + N_r + N_{pr} \qquad \text{(II-49)}$$

N. FIVE DEGREE-OF-FREEDOM EQUATIONS OF MOTION

Considering equations of motion for XR-3 test craft, the yaw (ψ) is defined as the rotational motion of the craft coordinate system relative to the fixed frame and the positive ψ angle is measured in the clockwise direction. This sign convention is in agreement with the rudder order sign definition. Since positive rudder angle corresponds to turning to the left, producing negative yaw moment and finally at the equilibrium condition, the negative yaw moment is generated.

Assuming small values of pitch (θ) and roll angles and relating heave motion to the free surface, the relationship between the fixed and craft coordinate system can be written. Eliminating the terms related to the fixed coordinate system, the simplified 5 DOF equations of motion are obtained as follows;

$$m \dot{v} = Y \tag{II-50}$$

$$m \dot{w} = Z \tag{II-51}$$

$$I_{xx} \dot{p} - I_{xz} \dot{r} = K \tag{II-52}$$

$$I_{yy} \dot{q} = M \tag{II-53}$$

$$I_{zz} \dot{r} - I_{xz} \dot{p} = N \tag{II-54}$$

The right hand sides of the equations of motion give the forces and moments acting on the craft in terms of the craft in terms of the craft coordinate system variables. In equation (II-57) $\dot{w}$ represents heave acceleration and all other variables in these equations have already been defined.

In order to develop a 5 DOF linear model, only the surge equation of motion (x-direction) is neglected. Since from 6 DOF nonlinear simulation results, very small velocity reduction is observed during the turn maneuver of the XR-3 test craft (over the speed range 20 through 30 knots).

III. LINEARIZATION OF THE EQUATIONS

A. TAYLOR SERIES EXPANSION AND TOTAL DIFFERENTIAL

Generally, the linearization process can be performed by means of a Taylor series expansion using the linear part of the series (omitting high order terms). The same process can be easily done applying a total differential to the net force and moment equations, since the effect of small disturbances to the system is to be determined.

The total differential of a given dependent variable A with respect to the independent variables x, y and z is given as

$$dA = \frac{\partial A}{\partial x} dx + \frac{\partial A}{\partial y} dy + \frac{\partial A}{\partial z} dz \qquad \text{(III-1)}$$

B. LINEARIZATION OF THE EQUATIONS OF MOTION AND AIR FLOW DYNAMICS

The total differentials of the equations of motion and air flow dynamics have been derived as

$$d\dot{w} = dZ/m \qquad \text{(III-2)}$$

$$d\dot{q} = dM/I_{yy} \qquad \text{(III-3)}$$

$$d\dot{m}_b = -[\rho_a \, n \, k_P + C_n \, A_\ell (\frac{\rho_a}{2\bar{P}_b(0)})^{1/2}] d\bar{P}_b \qquad \text{(III-4)}$$

$$d\dot{v} = dY/m \qquad \text{(III-5)}$$

where $\overline{P}_b(0)$ represents the steady state value of the plenum gauge pressure according to the final equilibrium condition.

The equations (II-52) and (II-54) both involved second order yaw and roll acceleration terms. Therefore applying the total differential and solving these two equations for $d\dot{p}$ and $d\dot{r}$ we have

$$d\dot{r} = dK/I + dN/I_r \tag{III-6}$$

$$d\dot{p} = dK/I_k + dN/I \tag{III-7}$$

I, I_r and I_k are defined as

$$I \triangleq \frac{I_{xx} I_{zz} - I_{xz}^2}{I_{xz}} \tag{III-8(a)}$$

$$I_r \triangleq \frac{I_{xx} I_{zz} - I_{xz}^2}{I_{xx}} \tag{III-8(b)}$$

$$I_k \triangleq \frac{I_{xx} I_{zz} - I_{xz}^2}{I_{zz}} \tag{III-8(c)}$$

Equation (III-6) and equation (III-7) contain both net incremental roll (dK) and yaw (dN) moments. This is simply a cross product inertial term (I_{xz}) effect in the equations of motion.

In equation (II-59), $d\overline{P}_b$ is not a state variable, it can be considered as an output variable, therefore from equation (II-26) and (II-27), $d\overline{P}_b$ must be

$$d\overline{P}_b = \frac{\partial \overline{P}_b}{\partial z} dz + \frac{\partial \overline{P}_b}{\partial m_b} dm_b$$

C. FIVE DEGREE-OF-FREEDOM LINEAR MODEL SENSITIVITY COEFFICIENTS

The sensitivity coefficients related to the right hand side of the equations of motion are defined as the partial derivatives of the net forces and moments divided by craft mass or inertial terms.

In [2], Barnes has developed a 2 DOF (heave and pitch) linear XR-3 model. Therefore most of the neave and pitch sensitivity coefficients are directly used in order to develop a 5 DOF linear model. However some modification is made for plenum sensitivity coefficients and pitch mode. Also some of the steady state operating point values have been reinvestigated using the 6 DOF nonlinear model.

In all the linearized equations, the final steady state values of the variables have been used.

1. Pitch and Heave Sensitivity Coefficients

In [2] equation (III-40), the sensitivity coefficient due to z has been redefined as

$$DHPZ = - A_b(0) \frac{\partial \overline{P}_b}{\partial z} + \overline{P}_b(0) \frac{b_w \ell_9}{h}$$

This is claculated from (II-22) where the second term does not appear in [2].

The modified form of the plenum pitch sensitivity coefficient due to state variable z is to be

$$DPPBZ = - Z_p(0) \frac{\ell_9}{2h} - X_{cp}(0) \bar{P}_b(0) \frac{b_w \ell_9}{h}$$

The derivation of these modified equations is based upon the total differential of the plenum lift force, it is

$$dZ_p = \frac{\partial Z_p}{\partial \bar{P}_b} d\bar{P}_b + \frac{\partial Z_p}{\partial A_b} dA_b$$

From equations (II-9), (II-26) and (II-27), the total differentials dV_b and $d\bar{P}_b$ have been calculated as

$$dV_b = -(A_b(0) - \ell_d(0) \frac{b_w \ell_9}{h}) dz \qquad \text{(III-9)}$$

$$d\bar{P}_b = \gamma P_b(0) [\frac{dM_b}{M_b(0)} + \frac{1}{V_b(0)}(A_b(0) - \ell_d(0) \frac{b_w \ell_9}{h})]dz . \qquad \text{(III-10)}$$

$d\bar{P}_b$ and dV_b equations are also different from the equations derived in [2].

The bow and aft seal pitch moments sensitivity coefficients (DPSFTH and DPSATH) due to θ and plenum air mass equation (AMB) are rederived and their modified forms are used for the pitch mode in the 5 DOF linear model computer program.

Considering the 5 DOF linear model state space matrix representation, the a_{ij}'s represent "A" matrix elements. Therefore the a_{ij} values relating to the sensitivity coefficients for heave motion are determined as

$$a_{21} = DZZ$$

$$a_{23} = DZTH$$

$$a_{24} = DZDP$$

$$a_{25} = DZMB$$

where DZZ, DZTH, etc., have been derived in [2]. However their modified forms can be found in the 5 DOF linear computer program.

For pitch motion, a_{ij} coefficients are

$$a_{41} = DTHZ$$

$$a_{43} = DTHTH$$

$$a_{44} = DTHDTH$$

$$a_{45} = DTHMB$$

2. Plenum Air Flow Sensitivity Coefficients

These coefficients are calculated directly from [2]. The a_{ij}'s related to plenum air sensitivity coefficients are

$$a_{51} = DMBZ$$

$$a_{55} = DMBMB$$

3. Sway Sensitivity Coefficients

Before deriving the sensitivity coefficients for sway motion, some partial derivatives related to the rudder and sidewall hydrodynamics must be calculated. From equation (II-11(b)) Y_r is already known, this follows the partial derivatives of Y_r with respect to the state variables

$$R_p = \frac{\partial Y_r}{\partial p} = C_t (C_e/u)\ Z_s \qquad \text{(III-11)}$$

$$R_v = \frac{\partial Y_r}{\partial v} = -\ C_t (C_e/u) \qquad \text{(III-12)}$$

$$R_r = \frac{\partial Y_r}{\partial r} = -\ C_t (C_e/u)\ X_r \qquad \text{(III-13)}$$

From equation (II-39), the sidewall cross flow drag terms D_{sw} partials are derived in the following equations.

Let us define first some coefficients

$$d_1 \triangleq \frac{1}{2}\,\rho\, C_d\, \ell$$

$$d_r \triangleq \ell_d(0) + \text{sign}(V_r)\ b_o\ \phi(0)$$

The partials are

$$D_z = \frac{\partial D_{sw}}{\partial z} = -\ d_1\ \text{sign}(V_r)\ V_r^{\,2}(0) \qquad \text{(III-14)}$$

$$D_\phi = - d_1 V_r^2(0)\ b_o \tag{III-15}$$

$$D_p = 2\ d_1\ d_r\ \mathrm{sign}(V_r)\ V_r(0)(Z_s - \ell_d(0)/2) \tag{III-16}$$

$$D_v = - 2\ d_1\ d_r\ V_r(0) \tag{III-17}$$

$$D_r = - 2\ d_1\ d_r\ \mathrm{sign}(V_r)\ V_r(0)\ X_s \tag{III-18}$$

d_2 and d_3 are defined as

$$d_2 \triangleq 2\ A_{33}\ b_o^2\ u \tag{III-19}$$

$$d_3 \triangleq A_{22}\ u \tag{III-20}$$

where u is the craft speed assumed to be constant.

For sway mode, the state matrix elements are

$$a_{96} = \frac{1}{m}\left(\frac{\partial Y}{\partial \phi}\right) = \frac{1}{m}(D_\phi \sin \beta) \tag{III-21}$$

where D_ϕ is given from equation (III-15).

$$\begin{aligned} a_{97} &= \frac{1}{m}\left(\frac{\partial Y}{\partial p}\right) \\ &= \frac{1}{m}[R_p + (R_p + d_3 Z_s)\sin \beta + d_3 Z_s] \end{aligned} \tag{III-22}$$

$$a_{99} = \frac{1}{m}\left(\frac{\partial Y}{\partial v}\right)$$

$$= \frac{1}{m}[R_v + (D_v - d_3)\sin\beta - d_3] \qquad \text{(III-23)}$$

$$a_{911} = \frac{1}{m}\left(\frac{\partial Y}{\partial r}\right)$$

$$= \frac{1}{m}[R_r + (D_r - d_3 x_s)\sin\beta - d_3 X_s - mu] \qquad \text{(III-24)}$$

4. <u>Roll and Yaw Sensitivity Coefficients</u>

Recalling equations (III-6) and (III-7), the net roll and yaw moments appear in both equations of motion. In this case, to determine sensitivity coefficients is not easy, since the yaw and roll partials are involved in the dynamic equation with different inertial terms and coefficients.

In order to simplify the problem, the roll and yaw partial derivatives are calculated individually, then combining these coefficients and dividing by corresponding inertial terms give the system sensitivity coefficients for the roll and yaw modes.

a. Roll Mode

The net roll partial derivatives are defined by k_{ij} variables.

The partial derivative with respect to z is

$$k_{71} = \frac{\partial K}{\partial z} = \frac{\partial}{\partial z}(K_{sf} + K_{sa} + K_{bf} + K_{ba}) \qquad \text{(III-25)}$$

In equation (III-26) all roll components have already been derived in the preceding sections.

From equations (II-30) and (II-31), the seal partials are

$$\frac{\partial K_{sf}}{\partial z} = - \left(\frac{b_o}{2.3}\right)^3 \rho\, g (1/\sin 31°)\ \phi(0)$$

$$\frac{\partial K_{sa}}{\partial z} = - \left(\frac{b_o}{2.3}\right)^3 \rho\, g (1/\sin 32°)\ \phi(0)$$

For buoyancy partials, let us define the following coefficients;

$$b_1 \triangleq 2 \rho g \ell_1 \tag{III-26}$$

$$b_2 \triangleq 2 \rho g \ell_2 \tag{III-27}$$

$$b_3 \triangleq \left(\frac{b_f + b_w}{2}\right) + \frac{\ell_f}{2 \tan \beta_1} \tag{III-28}$$

$$b_4 \triangleq \frac{\ell_f}{\tan \beta_1} + b_f \tag{III-29}$$

$$b_6 \triangleq \frac{\ell a}{\tan \beta_2} + b_a \tag{III-30}$$

From equations (II-35) and (II-36), the buoyancy partials are

$$\frac{\partial K_{bf}}{\partial z} = - \frac{b_1\ b_3}{\tan \beta_1}(b_5 + b_3)\ \phi(0)$$

$$\frac{\partial K_{ba}}{\partial z} = - \frac{b_2\ b_4}{\tan \beta_2}(b_6 + b_4)\ \phi(0)$$

Equation (II-26) follows;

$$\frac{\partial K_p}{\partial z} = -[A_b(0)\ \overline{P}_b(0) + (Z_s - \ell_d(0)\ \frac{\partial \overline{P}_b}{\partial z}]\ \phi(0)$$

Similarly for sidewall cross flow drag partial is

$$\frac{\partial K_d}{\partial z} = D_z(b_o \cos\beta - Z_o \sin\beta)$$

The roll partial derivatives with respect to θ are

$$k_{73} = \frac{\partial K}{\partial \theta}$$

$$= \frac{\partial}{\partial \theta}(K_{sf} + K_{sa} + K_{bf} + K_{ba}) \qquad \text{(III-31)}$$

where

$$\frac{\partial K_{sf}}{\partial \theta} = (\frac{b_w}{2.3})^3\ \rho\ g(\ell_3/\sin 31°)\ \phi(0)$$

$$\frac{\partial K_{sa}}{\partial \theta} = -\ (\frac{b_w}{2.3})^3\ \rho\ g(\ell_4/\sin 32°)$$

$$\frac{\partial K_{bf}}{\partial \theta} = \frac{b_1\ b_2}{\tan\beta_1}(b_5 + b_3\ \ell_5)\ \phi(0)$$

$$\frac{\partial K_{ba}}{\partial \theta} = -\ \frac{b_2\ b_4}{\tan\beta_2}(b_6 + b_4\ \ell_3)\ \phi(0)$$

The roll partial derivative with respect to M_b is

$$k_{75} = \frac{\partial K_p}{\partial M_b}$$

$$= A_b(0)\left(Z_s - \ell_d(0)\right) \frac{\partial \bar{P}_b}{\partial M_b} \phi(0) \qquad \text{(III-32)}$$

The roll partials with respect to ϕ are

$$k_{76} = \frac{\partial K}{\partial \phi}$$

$$= \frac{\partial}{\partial \phi}(K_{sf} + K_{sa} + K_{bf} + K_{ba} + K_p + K_d) \qquad \text{(III-33)}$$

where

$$\frac{\partial K_{sf}}{\partial \phi} = -(b_w/2.3)^3 \rho g X_f$$

$$\frac{\partial K_{sa}}{\partial \phi} = -(b_w/2.3)^3 \rho g X_a$$

$$\frac{\partial K_{bf}}{\partial \phi} = -b_1 b_3^2 b_5$$

$$\frac{\partial K_{ba}}{\partial \phi} = -b_2 b_4^2 b_6$$

$$\frac{\partial K_p}{\partial \phi} = \bar{P}_b(0)\ (Z_s - \ell_d(0))\ \ell\ b_w$$

$$\frac{\partial K_d}{\partial \phi} = D_\phi (b_o \cos \beta - Z_o \sin \beta)$$

The roll partials with respect to p are

$$k_{77} = \frac{\partial K}{\partial p}$$

$$= \frac{\partial}{\partial p}(K_{sw} + K_d + K_r) \qquad \text{(III-34)}$$

where

$$\frac{\partial K_{sw}}{\partial p} = - d_2 - Z_s^2 A_{22} u - 32/\pi \; b_o^2 B_c$$

$$\frac{\partial K_d}{\partial p} = (D_p + \frac{\partial Y_{sw_1}}{\partial p}) (b_o \cos \beta - Z_o \sin \beta)$$

The roll partials with respect to V are

$$k_{79} = \frac{\partial K}{\partial V}$$

$$= \frac{\partial}{\partial V} (K_{sw} + K_d + K_r) \qquad \text{(III-35)}$$

where

$$\frac{\partial K_d}{\partial V} = (D_v - d_3)(b_o \cos \beta - Z_o \sin \beta) + d_3 X_s Z_s$$

$$\frac{\partial K_{sw}}{\partial V} = d_3 Z_s$$

$$\frac{\partial K_r}{\partial V} = C_t (C_e/u)\ Z_r$$

The roll partials with respect to yaw rate are

$$k_{711} = \frac{\partial K}{\partial r}$$

$$= \frac{\partial}{\partial r}(K_{sw} + K_d + K_r) \qquad \text{(III-36)}$$

where

$$\frac{\partial K_{sw}}{\partial r} = d_3\ X_s\ Z_s$$

$$\frac{\partial K_{sw}}{\partial r} = (D_r - d_3 X_s)(b_o \cos \beta - Z_o \sin \beta)$$

$$\frac{\partial K_r}{\partial r} = C_t (C_e/u)\ X_r\ Z_r$$

b. Yaw Mode

The following coefficients are defined for yaw rotational motion;

$$n_1 \triangleq 2\ A_{22}\ \ell(1 - \lambda) \qquad \text{(III-37)}$$

$$n_2 \triangleq -\ \pi/5\ \rho\ u\ \ell \qquad \text{(III-38)}$$

$$n_3 \triangleq -\ \text{sign}(V_r)\ \rho\ C_d\ \ell_d(0) \qquad \text{(III-39)}$$

$$C_1 \triangleq 2\, S_1\, \ell^3 \tag{III-40}$$

$$C_2 \triangleq S_2\, \ell^2 \tag{III-41}$$

$$X_w \triangleq -\,1/2\, \rho\, C_f\, u^2\, \ell \tag{III-42}$$

The net yaw partial derivatives are defined by n_{ij} variables.

The yaw partials with respect to ϕ are

$$\begin{aligned} n_{116} &= \frac{\partial N_{sw}}{\partial \phi} \\ &= \frac{\partial N_1}{\partial \phi} + \frac{\partial}{\partial \phi}(X_{pw} - X_{sw})\; b_o \end{aligned} \tag{III-43}$$

where

$$\frac{\partial N_1}{\partial \phi} = 4\, n_2\, V(0)\, b_o^{\,2}\, \phi(0)$$

$$\frac{\partial}{\partial \phi}(X_{pw} - X_{sw}) = -\,4\, X_w$$

The yaw partials with respect to p are

$$n_{117} = \frac{\partial N}{\partial p} = \frac{\partial}{\partial p}(N_{sw} + N_r) \tag{III-44}$$

The N_{sw} and N_r partial derivatives can be calculated from equations (II-44(a)) and (II-11(d)).

The yaw moments partial derivatives with respect to V and r are derived similarly, the n_{ij} coefficients related to these modes are

$$n_{119} = \frac{\partial N}{\partial V} \tag{III-45}$$

$$n_{1111} = \frac{\partial N}{\partial r} \tag{III-46}$$

c. Roll Sensitivity Coefficients

The roll sensitivity coefficients corresponding to state matrix elements a_{ij}'s are determined from equation (III-7). They are

$$a_{71} = k_{71}/I_k$$

$$a_{73} = k_{73}/I_k$$

$$a_{75} = k_{76}/I_k$$

$$a_{76} = k_{76}/I_k + n_{116}/I$$

$$a_{77} = k_{79}/I_k + n_{119}/I$$

$$a_{711} = k_{711}/I_k + n_{1111}/I$$

where inertial terms I and I_k are found from equations (III-8(a)) and (III-8(c)).

d. Yaw Sensitivity Coefficients

For yaw motion, the sensitivity coefficients a_{ij}'s have been determined from equation (III-6).

These coefficients are listed below;

$$a_{111} = k_{71}/I$$

$$a_{113} = k_{73}/I$$

$$a_{115} = k_{75}/I$$

$$a_{116} = k_{76}/I + n_{116}/I_r$$

$$a_{117} = k_{79}/I + n_{119}/I_r$$

$$a_{1111} = k_{711}/I + n_{1111}/I_r$$

where the inertial term I_r is calculated from equation (III-8(b)).

D. STATE SPACE REPRESENTATION AND OUTPUT EQUATION

The state vector of the linear 5 DOF model is shown as

$$X = [dZ\ dW\ d\theta\ dq\ dM_b\ d\phi\ dp\ dy\ dV\ d\psi\ dr]^T \qquad \text{(III-47)}$$

Then, the system state equation must be

$$\dot{X} = Ax + Bu \qquad \text{(III-48)}$$

And the output equation is

$$y = C\ X \tag{III-49}$$

"A" matrix elements have already been determined. However for "B" matrix elements, the step input to the system can be considered as a weight removal disturbance and for the roll and yaw modes, a rudder order disturbance.

For weight removal forcing function, the input is to be

$$b_{21} = \frac{W_f - W_i}{m} \tag{III-50}$$

where

W_f = final craft weight

W_i = initial craft weight

m = craft mass corresponding to the final weight W_f.

When the rudder order is used, sway, roll and yaw forcing functions are generated as follows;

sway $$b_{91} = \frac{1}{m}(2\ X_t \sin \delta_r + C_t\ \delta_r) \tag{III-51}$$

roll $$b_{71} = (2\ X_t \sin \delta_r + C_t\ \delta_r)(-\ z_r/I_k + x_r/I)$$

yaw $$b_{111} = (2\ X_t \sin \delta_r + C_t\ \delta_r)(x_r/I_r + z_r/I)$$

Finally, defining state variables x_1, x_2, ..., etc., the state equations of the 5 DOF linear model are given as follows;

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = a_{21}x_1 + a_{23}x_3 + a_{24}x_4 + a_{25}x_5$$

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = a_{41}x_1 + a_{43}x_3 + a_{44}x_4 + a_{45}x_5$$

$$\dot{x}_5 = a_{51}x_1 + a_{55}x_5$$

$$\dot{x}_6 = x_7$$

$$\dot{x}_7 = a_{71}x_1 + a_{73}x_3 + a_{75}x_5 + a_{76}x_6 + a_{77}x_7 + a_{79}x_9 + a_{711}x_{11}$$

$$\dot{x}_8 = x_9$$

$$\dot{x}_9 = a_{96}x_6 + a_{97}x_7 + a_{99}x_9 + a_{911}x_{11}$$

$$\dot{x}_{10} = x_{11}$$

$$\dot{x}_{11} = a_{111}x_1 + a_{113}x_3 + a_{115}x_5 + a_{116}x_6$$

$$+ a_{117}x_7 + a_{119}x_9 + a_{1111}x_{11}$$

All coefficients of the state equations are defined in the preceding sections.

Considering outputs of the linear model, only incremental changes of the variables can be observed.

IV. LINEAR FIVE DEGREE-OF-FREEDOM COMPUTER PROGRAM DESCRIPTIONS

The Digital Simulation Language (DSL/360) is used for the linear 5 DOF XR-3 computer program. Eleven first order integrator blocks are needed for five degree of freedom simulations and for all linear runs, fourth order Runge-Kutta with fixed interval integration method is selected.

In addition to the craft dimensional values, initial and final steady state operating points are entered into the program for linearization purposes and plot outputs.

The input parameters of this program are

V	=	Craft speed (ft/sec)
WF	=	Final craft weight (lb)
W	=	Initial craft weight (lb)
RUDANG	=	Rudder input (positive for port turn)
DR	=	Average deadrise angle
PBBAR	=	Final steady state value of plenum pressure (lb/ft^2)
ALD	=	Final steady state craft draft (inches)
PHI	=	Final steady state roll angle
FYP	=	The propulsion system thrust corresponding to the craft speed (for each of propellers)
VL	=	Steady state lateral speed (ft/sec)
R	=	Steady state yaw rate (rad/sec).

The steady state values of the variables are determined from 6 DOF nonlinear model simulations.

V. SIX DEGREE-OF-FREEDOM NONLINEAR MODEL SIMULATIONS

In this chapter 6 DOF nonlinear model simulations are discussed.

At first, some of the runs are made in order to determine craft initial steady state operating point corresponding to craft speed and thrust inputs. Since 6 DOF model weight transient response can be analyzed by means of entering proper craft initial values into the program, this is simply an initial condition response of the nonlinear dynamic system.

A. WEIGHT REMOVAL TRANSIENT

For 30 and 20 knot craft speeds, the steady state values of some variables are listed in Table I.

Table I

Steady State Values of the Weight Removal Response

Speed (knt)	Pitch (degree)	$\overline{P}_b$ (lb/ft^2)	Draft (inch)	Thrust (lb)	Weight (lb)
30	0.95	24.8	8.6	355.6	6722
30	0.26	24.8	5.6	287.8	6050
20	0.45	24.8	6.06	186.2	6050

For 30 knot craft speed, two different steady state pitch angles are observed corresponding to the different weights. In [2] for pitch transient response, 0.65° steady state pitch angle value has been used for both linear and nonlinear

simulations. On the other hand as seen in Table I, 0.26° and 0.95° steady state pitch values are obtained. This disagreement may be explained by noting that different dimensional values were used or more probably a different modified 6 DOF computer program deck was used.

For 6050 lb craft weight, the steady state pitch angle 0.26° is in agreement with the value determined by Menzel in figure 6 in [6].

During the weight removal response, simulations of 6 DOF, two different stern seal base leakage areas are used. In [1] a smaller leakage area is assumed for the linear heave only model as $A_\ell = 0.384$. However $A_\ell = 3.84$ also has been simulated and it is understood that the smaller leakage area is more reasonable considering other steady state variables in the air flow dynamic equations (II-23) and (II-24). Since at the steady state condition $Q_{in} = Q_{out}$ must be satisfied, that permits only smaller A_ℓ for a given Q_o and $\overline{P}_b$ steady state values. Therefore $A_\ell = 0.384$ is preferred and used for nonlinear simulations.

B. TURNING MANEUVER

When the 3 DOF pitch, heave and roll linear model was developed, the 6 DOF nonlinear model simulations were used in order to determine all steady state roll moments during the turn maneuver. In addition to the roll moments, yaw and sway outputs were also investigated and the results are tabulated in Tables II, III and IV.

Table II

Steady State Roll Moments

(rudder = 5°, 30 knot speed)

Roll Moments	Positive	Negative
Stern seal FKSS	-	-2.2
Bow seal FKBS	-	-280.
Sidewall FKSW	-	-41.5
Rudder FKRUD	131.	-
Propulsion FKP	0.057	-
Aerodynamic FKAED	-	-22.7
Plenum ABPB*PHI*(-Z)	215.3	-

Table III

Steady State Yaw Moments

(rudder = 5°, 30 knot speed)

Yaw Moments	Positive	Negative
Stern seal FNBS	3.22	-
Bow seal FNSS	0.	0.
Sidewall FNSW	-	-482.2
Rudder FNRUD	532.65	-
Propulsion FNP	2.78	-
Aerodynamic FNAED	-	- 56.41

Table IV

Steady State Sway Forces

(rudder = 5°, 30 knot speed)

Sway Forces	Positive	Negative
Sidewall FYSW	-	-351.8
Rudder FYRUD	-	- 47.6
Aerodynamic FYAED	-	- 19.07
Centrifugal -R*U*AM	419.24	-

From Table II, it is understood that for a given (+) rudder input, the sign convention of the craft dynamics was in agreement with turning to the left. However, a negative sway displacement plot is observed for this maneuver. As a result, in the R.H.S. subroutine of the 6 DOF program, the sign correction should be done for y-displacement.

The steady state sway forces acting on the XR-3 test craft in a turn to the left are shown in figure 6. As seen in this figure and from Table IV, the rudder sway force is in the steady state condition. For a left turn, initially the rudder sway force is generated in the reverse direction and finally a negative steady state rudder sway force is produced. Further investigation is done in the RUDDER subroutine dynamic equations of the 6 DOF computer model, but no error has been determined in these equations. Also, different craft speeds and different effective rudder angle coefficients (ENDFAC) are used but everytime the same configuration is observed.

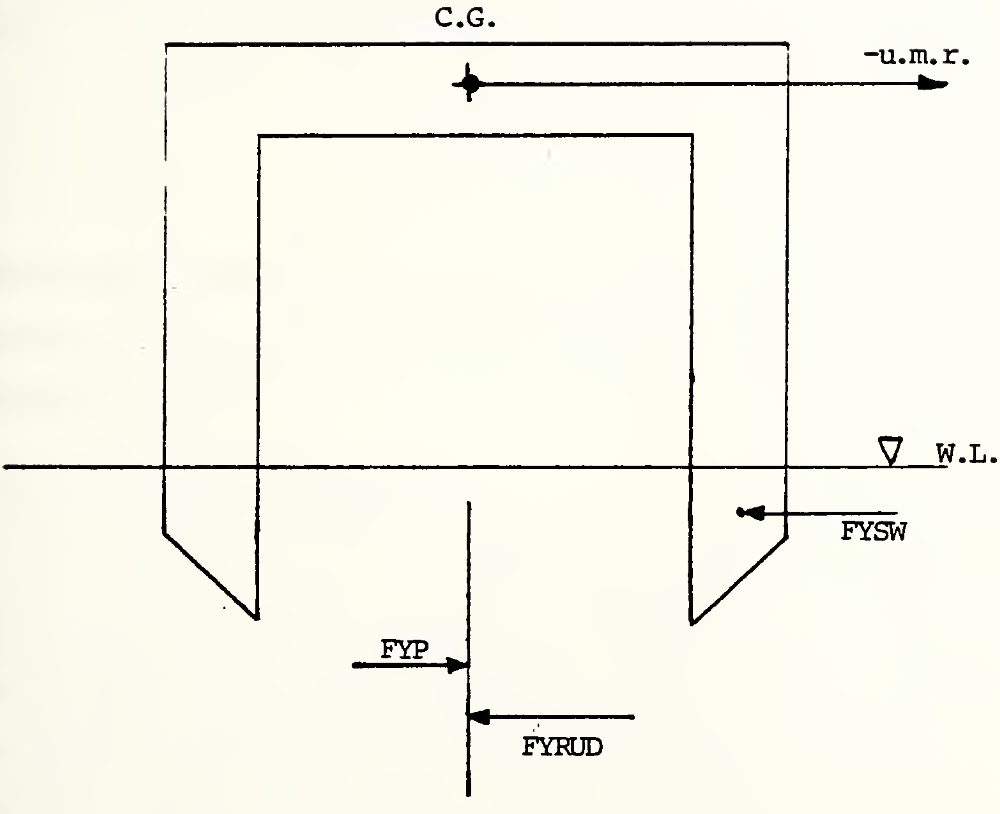


Figure 6. Steady state sway forces configuration at the left turn

In addition to rudder dynamics, the propulsion system of the XR-3 contributes to the roll, yaw and sway motions. However this contribution is not a dominant factor compared with the rudder effect.

For the XR-3 test craft propulsion system configuration, the direction of the thrust vector is also changed as well as the rudder deflection. As seen from Tables II, III and the simulations with different rudder order, it is understood that the propulsion thrust component due to the rudder order is not calculated properly, therefore the following modification is made in the PROPULSION subroutine of the 6 DOF program,

```
FYS  =  -STHSTS*CD+THSS*CD
```

where FYS represents the sway force due to the starboard propeller, and the others are defined in the propulsion subroutine program.

C. DEADRISE ANGLE EFFECT

As reported in [4], the deadrise angle has a major effect on the surface effect ship's roll behavior and therefore is an important design consideration. The deadrise angle effect on the roll motion has been investigated by Reidel in [3]. In this investigation, some arbitrary coefficients (PROMO 1, 2, etc.) are used for the vertical force component of the sidewall hydrodynamics. From this investigation, the conclusion reported by Reidel was that more damping could be obtained for the pitch and roll motions by changing the deadrise angle.

The deadrise effect is reinvestigated by simulating the system with different rudder orders including zero disturbance, then the heave forces due to sidewall hydrodynamics were compared to each others. As a result, no significant sidewall heave force change was observed. For instance, for 0° and 5° rudder inputs, the sidewall heave forces (FZSW) are found to be -568.8 and -568.05 respectively. This result is not acceptable, since in a turn maneuver, the cross flow drag is generated at the outboard sidewall, so the deadrise projection of cross flow drag must be contributed to the sidewall heave force. More investigation has been made in the SIDEWALL subroutine of the 6 DOF program and it has been determined that only the force component due to added mass given by equation (II-21) is projected as a lift force. Actually the cross flow drag component must be included to this projection, since the frontal area for cross flow drag component is outboard of the submerged section of the sidewall. Therefore it is concluded that the XR-3 test craft 6 DOF program SIDEWALL subroutine does not include effectively the lift force due to deadrise. On the other hand, the lift force and horizontal drag component can have different drag coefficients, therefore the modification of the sidewall subroutine is left for future studies.

VI. COMPARISON OF NONLINEAR AND LINEAR MODEL RESULTS

A. C.G. ACCELERATION (see figs. 9 and 23)

A 10% weight removal disturbance is used for both models. The linear and nonlinear model showed very rapid response with small rise time. As seen in figure 9, the 6 DOF model transient is relatively more damped compared with the linear model response. The linear model showed a small overshoot but it is also sufficiently damped. Small oscillatory behavior is observed in both figures which is due to pitch-heave coupling. In general the two models agree in transient response and steady state behavior.

Both of the C.G. acceleration curves were normalized by a factor "g", the gravitational constant.

B. PITCH TRANSIENT (see figs. 10 and 24)

As seen in these figures, both models showed an oscillatory transient response with the same frequency, $w \doteq 3.12$ rad/sec. However their steady state values are different. In fact, the pitch moment due to plenum pressure and the effective plenum pressure center play a dominant role for pitch motion. In [2] Barnes developed plenum modeling including effective plenum roof area calculations and plenum pressure centroid shift due to draft variation. Therefore the linear model plenum modeling is different from the nonlinear modeling, so that a greater plenum moment arm is calculated in the linear model.

The steady state pitch angle values are 0.5° and 0.75° for nonlinear and linear models correspondingly.

C. PLENUM PRESSURE TRANSIENT (see figs. 7 and 21)

As seen in these figures, both models are exactly in agreement with each other. In each curve, the plenum pressure suddenly drops to 21.6 (lb/ft^2) then increases up to its steady state value with sufficient damping. This is expected behavior because the plenum volume increases when 10% weight is removed, obviously this disturbance causes a sudden drop in plenum pressure. As seen before, pitch-plenum pressure coupling had been observed during the exponential increasing phase of the plenum pressure. At the fifth second of simulation time, nonlinear model plenum pressure is about 24.29 while the linear model pressure is 24.25.

D. DRAFT TRANSIENT (see figs. 8 and 22)

Excellent agreement was achieved between linear and non-linear model draft responses. As expected, the draft decreases exponentially when the weight is removed from the craft. The draft is found to be 5.7 inches for the linear model, 5.85 inches for the nonlinear model at the fifth second of simulation time.

As a result, both models exhibited the same draft responses.

E. ROLL RESPONSE

As mentioned before, at first a 3 DOF linear model (pitch-heave-roll) had been developed. 3 DOF linear and 6 DOF

nonlinear models roll behavior comparison is done by means of a step input roll moment disturbance to the linear model and a turning command to the nonlinear model. In figure 13 6 DOF nonlinear model roll angle response is shown for a 5° rudder order (left turn), in this simulation 1.18° outboard steady state roll angle is generated. From the R.H.S. subroutine of the 6 DOF program, all the steady state roll moment components are determined as seen in Table II and the sum of these disturbance moments applied to the linear model roll mode as a step input. Roll behavior is analyzed from figure 27. As expected, the linear model showed a greater overshoot and more oscillatory response compared with the nonlinear roll transient. Since the linear model has been disturbed by a step roll moment corresponding to the nonlinear model steady state roll moments. On the other hand, its steady state roll angle is found to be 1.28°. The roll steady state difference of two models is about 8.4%. For a 3° rudder input, nonlinear and linear simulations are obtained in figures 11 and 25 with the steady state values 0.62° and 0.65° respectively. Hence the difference is 4.8% in the steady state values for these simulations.

Figures 12 and 14 show XR-3 yaw rate plots and corresponding linear simulations are shown in figures 26 and 28.

As a result, the 3 DOF linear model and 6 DOF program roll simulations are in agreement with each other within 10% difference.

As discussed in the previous chapter, some problems are observed in the 6 DOF nonlinear program. Therefore developing two more modes for the 3 DOF model, the 5 DOF linear model has been generated. By means of this model, roll behavior of the XR-3 in a turn, deadrise angle and cross product inertial term effects have been investigated for 20 knot craft speed with different rudder deflections.

The roll response can be seen in figure 29 omitting the cross product inertial term (I_{xz} = -2800.) in the equations of motion, applying a 10° rudder order and assuming 70 degree average deadrise angle of the craft. For this particular test, the craft starts inboard rolling with the oscillatory transient then goes to 0.47° steady state roll. Using the same input parameters and also including the cross product term $\dot{I}_{xz}$ in the equations of motion, smaller overshoot (18%) and a more damped roll response has been observed in figure 31. As seen in this figure, at the initial phase, secondary overshoot has been generated. The steady state roll angle is 0.40° and the oscillation frequency w = 3.5 rad/sec., for this simulation. On the other hand, the corresponding 6 DOF nonlinear simulation is shown in figure 17 and also a roll rate plot is shown in figure 18. The nonlinear simulation in figure 17 shows a more damped transient but greater steady state roll behavior (1.32°) compared with the corresponding linear simulation shown in figure 31.

Figures 30 and 32 present linear simulation curves for 5 and 15 degree rudder inputs respectively. Both curves exhibit the same linear model response discussed before. Finally the linear and nonlinear model steady state responses are summarized as follows.

Rudder	6 DOF Nonlinear	5 DOF Linear	Reference
5	0.57	0.24	figures 15 and 30
10	1.32	0.40	figures 17 and 31
15	2.2	0.45	figures 19 and 32

The deadrise angle effect is investigated by using different deadrise angle values for 10 degree rudder input and 20 knot craft speed simulations. The results are tabulated in Table V.

Table V

Sidewall Deadrise Angle Effect

(rudder = 10°, 20 knot speed)

Deadrise angle (degree)	Roll angle (degree)	Lateral Speed (ft/sec)	Yaw rate (rad/sec)
45	-1.01	4.18	-0.064
50	-0.84	4.04	-0.069
55	-0.62	3.90	-0.076
60	-0.30	3.83	-0.080
65	0.02	3.73	-0.085
70	0.40	3.60	-0.100

For the linear model, the lateral velocity and yaw rate plots are shown in figures 33 and 34. Both of them showed sufficiently damped transient response. From figure 33, the lateral speed steady state value is found 3.6 (ft/sec) and as expected for turning to the left, the negative yaw rate is generated as -0.1 (rad/sec).

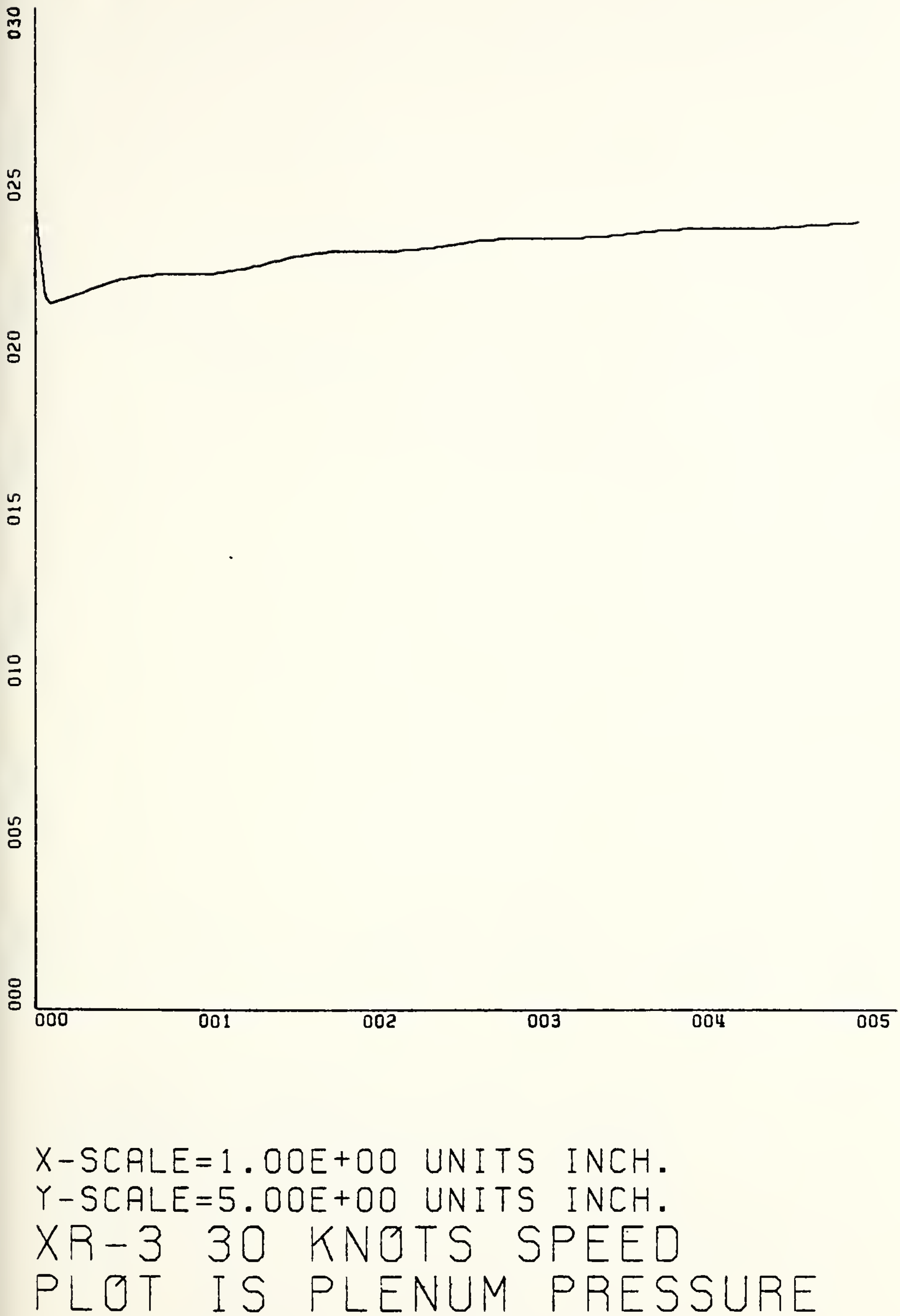
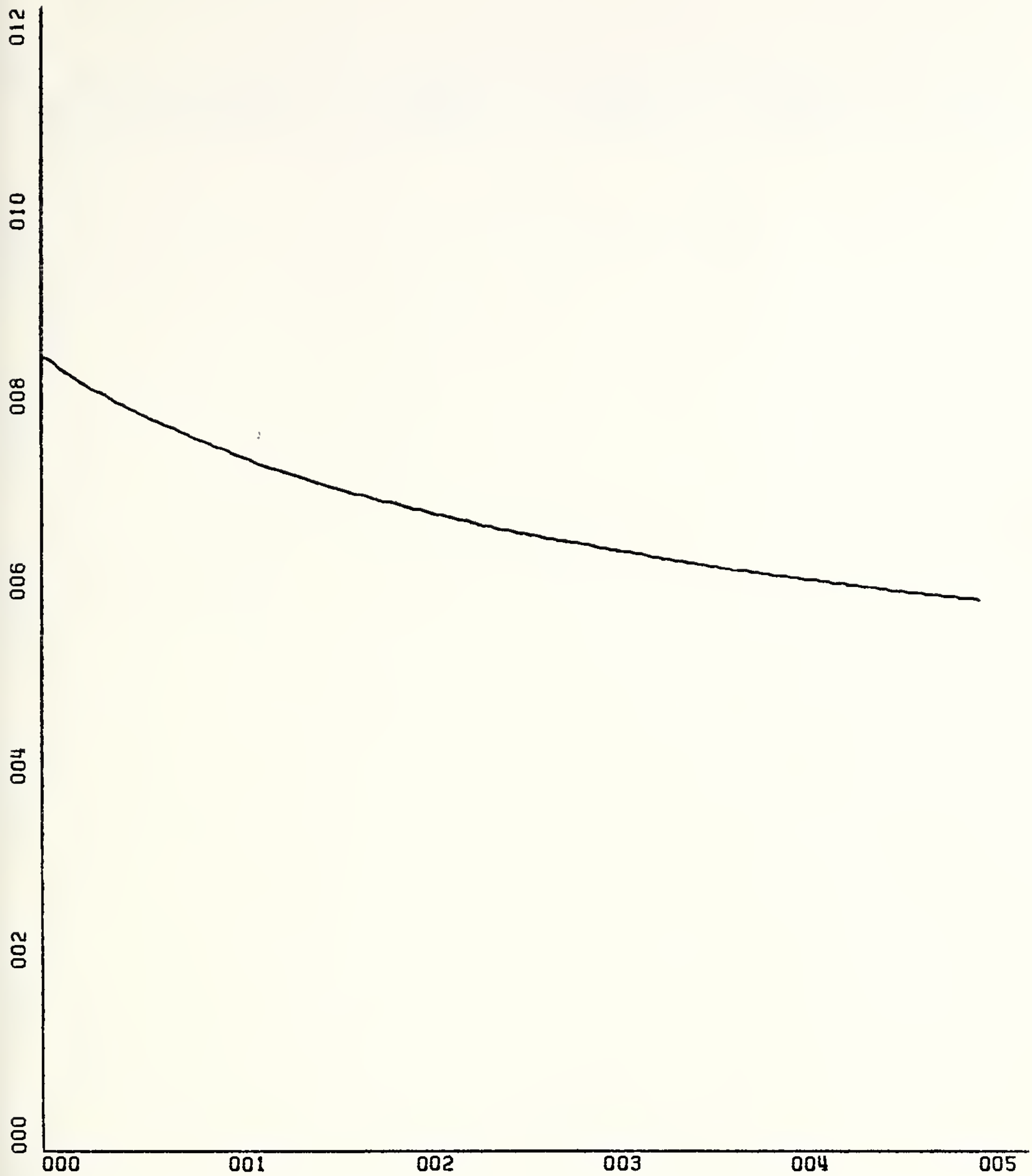


Figure 7. 6 DOF Plenum pressure transient



X-SCALE=1.00E+00 UNITS INCH.
Y-SCALE=2.00E+00 UNITS INCH.
XR-3 30 KNØTS SPEED
PLØT IS Z DISPLACEMENT

Figure 8. 6 DOF draft transient

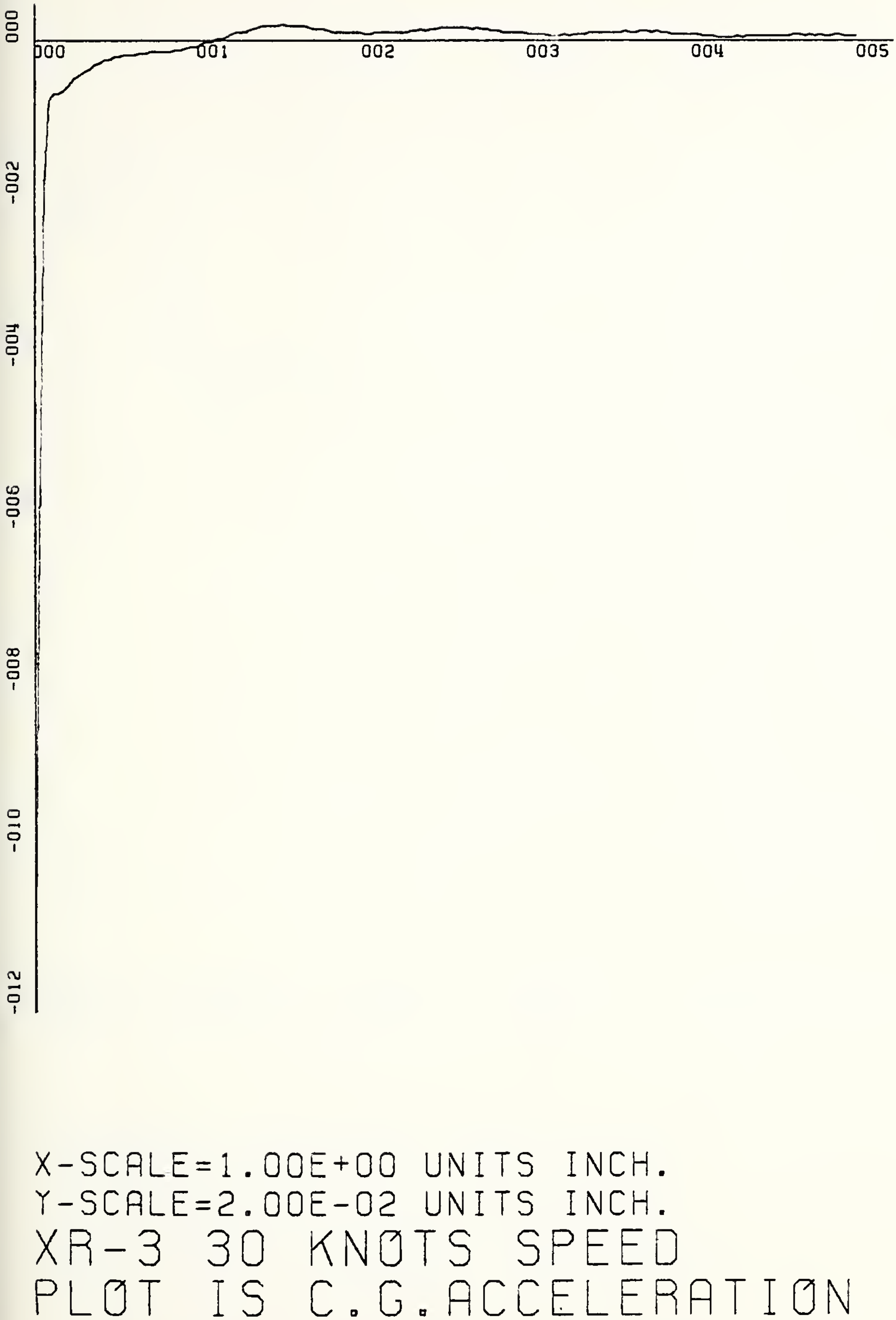


Figure 9. 6 DOF C.G. Acceleration

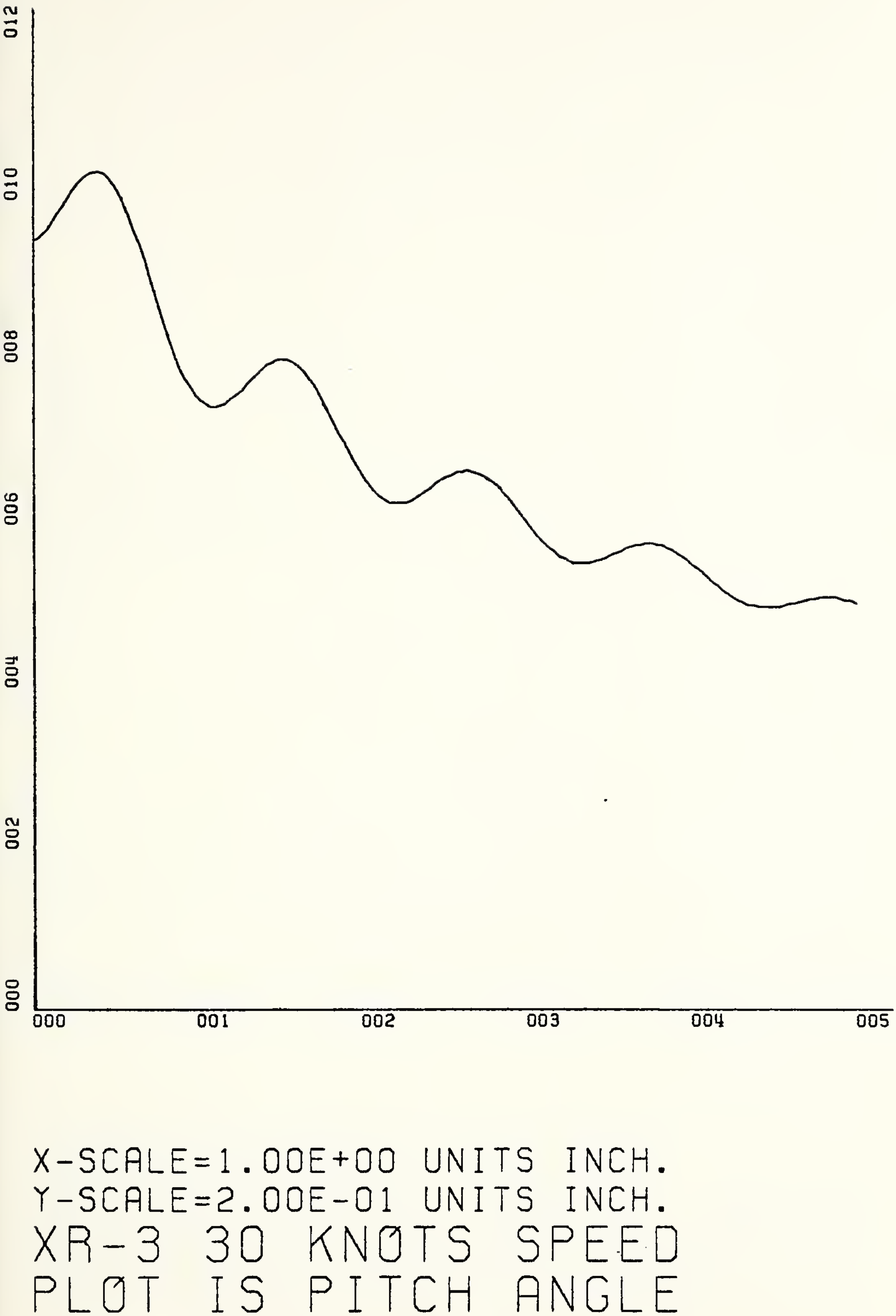
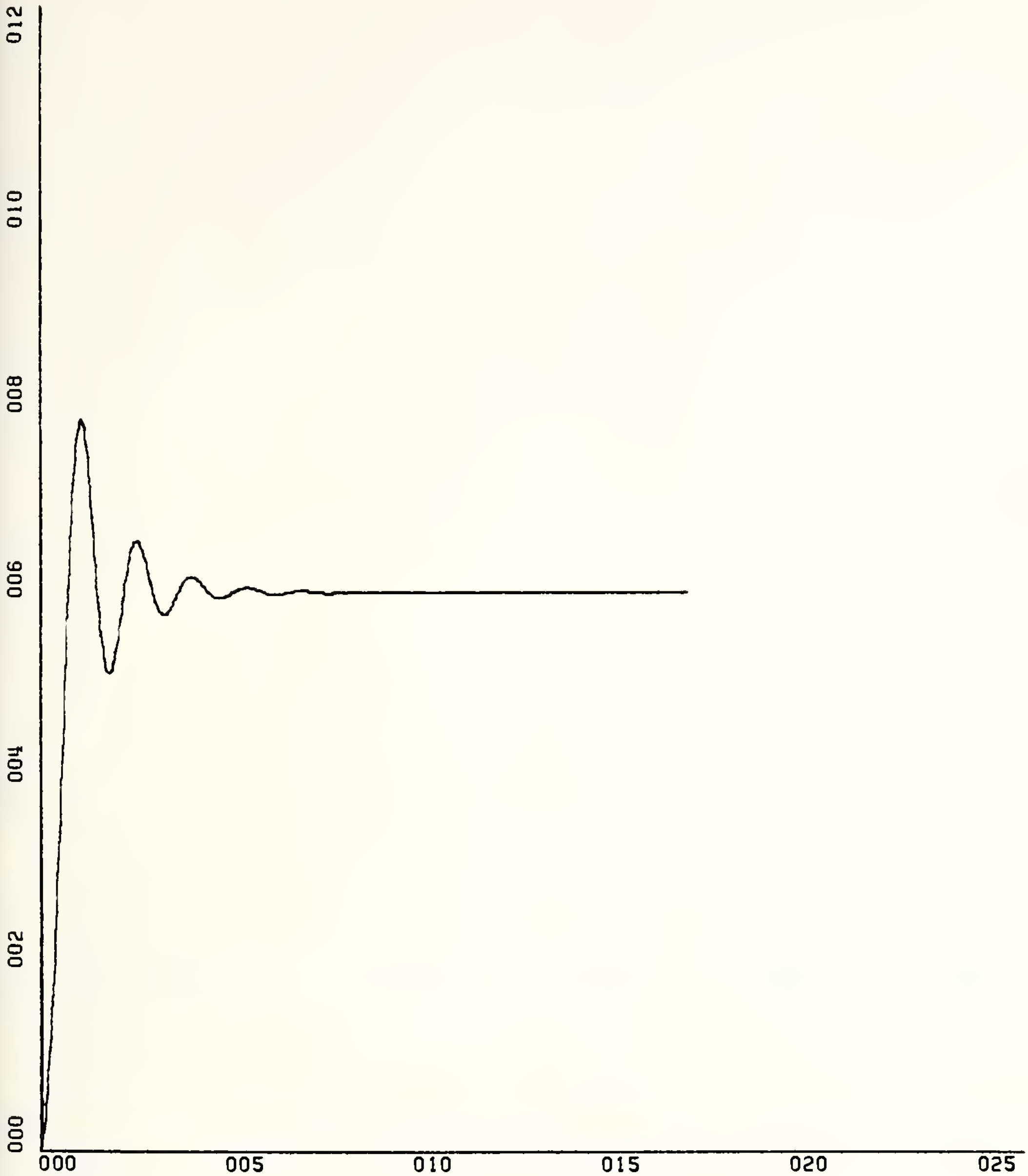


Figure 10. 6 DOF pitch angle transient



X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E-01 UNITS INCH.
XR-3 30 KNØTS SPEED RD=3
PLØT IS ROLL ANGLE

Figure 11. 6 DOF Roll angle plot, $\delta_r = 30°$
30 knot speed

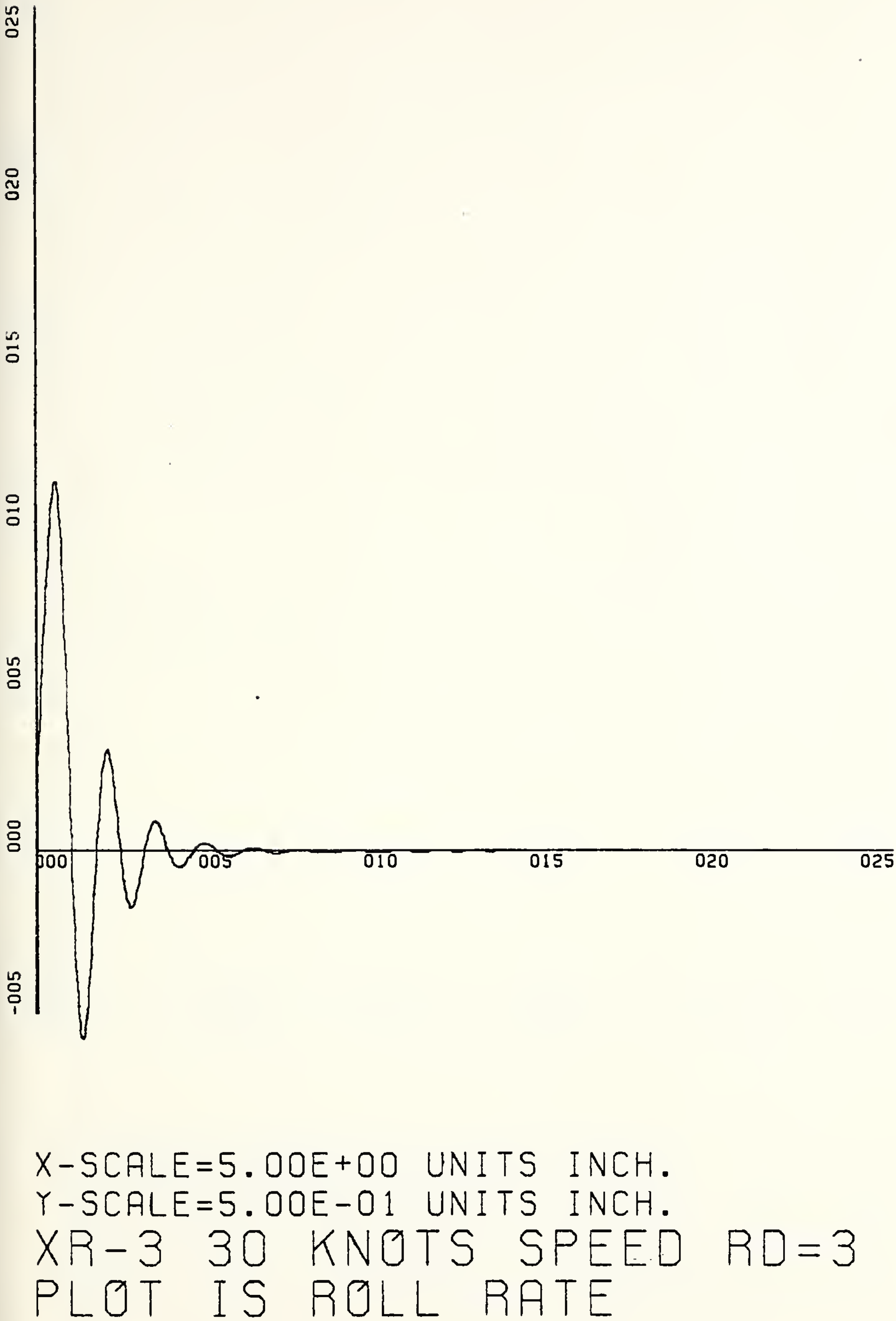


Figure 12. 6 DOF roll rate plot, $\delta_r = 3°$
30 knot speed

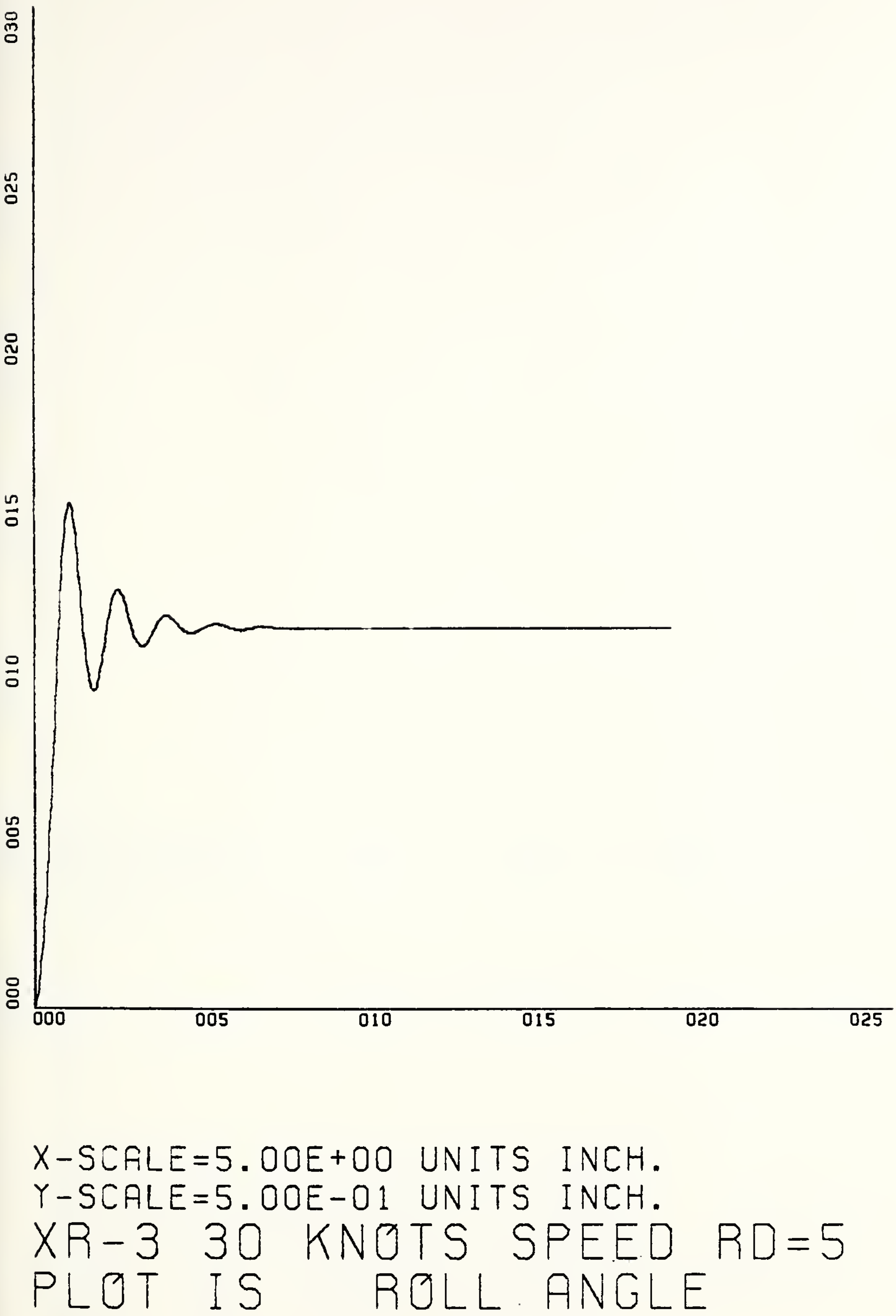
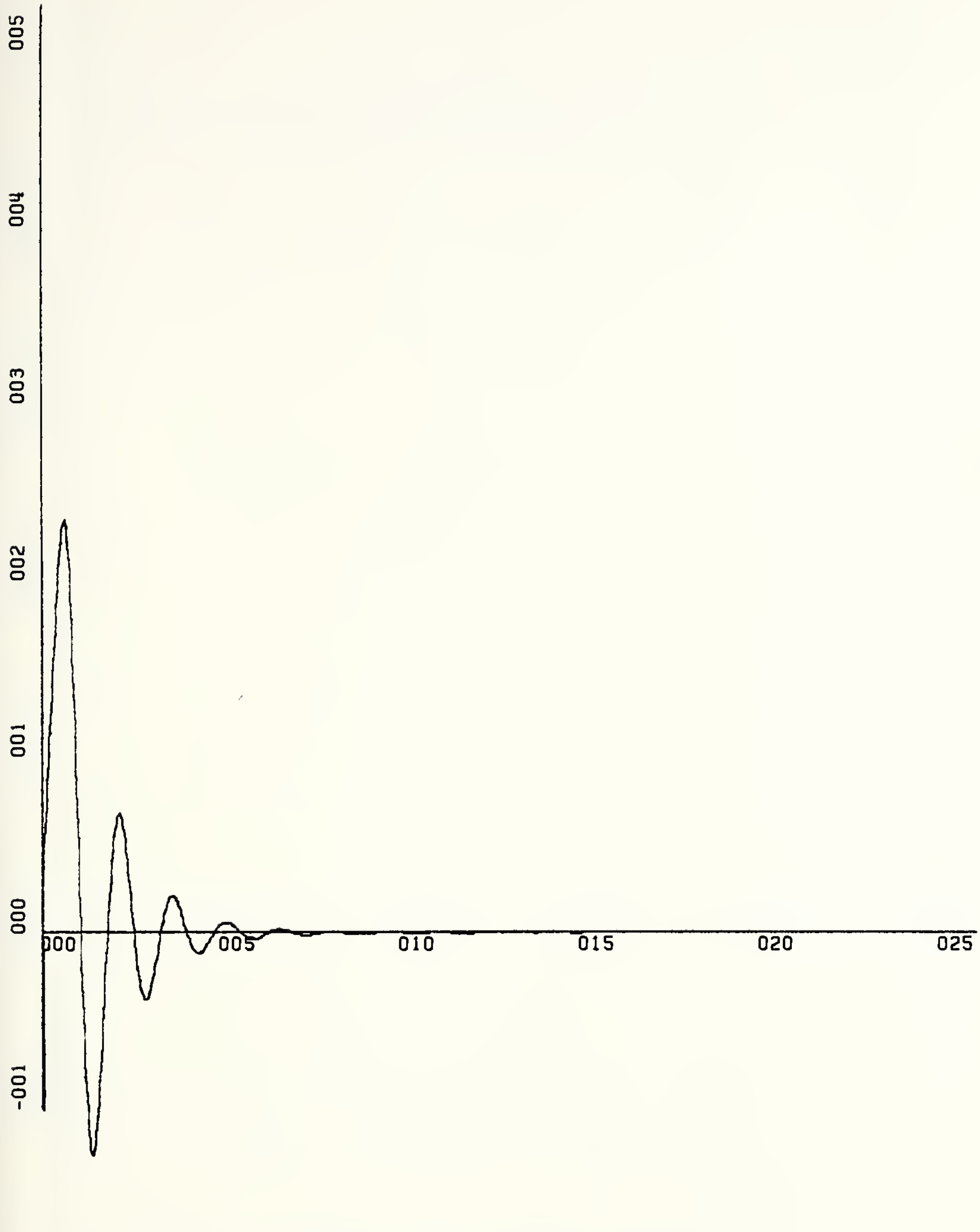
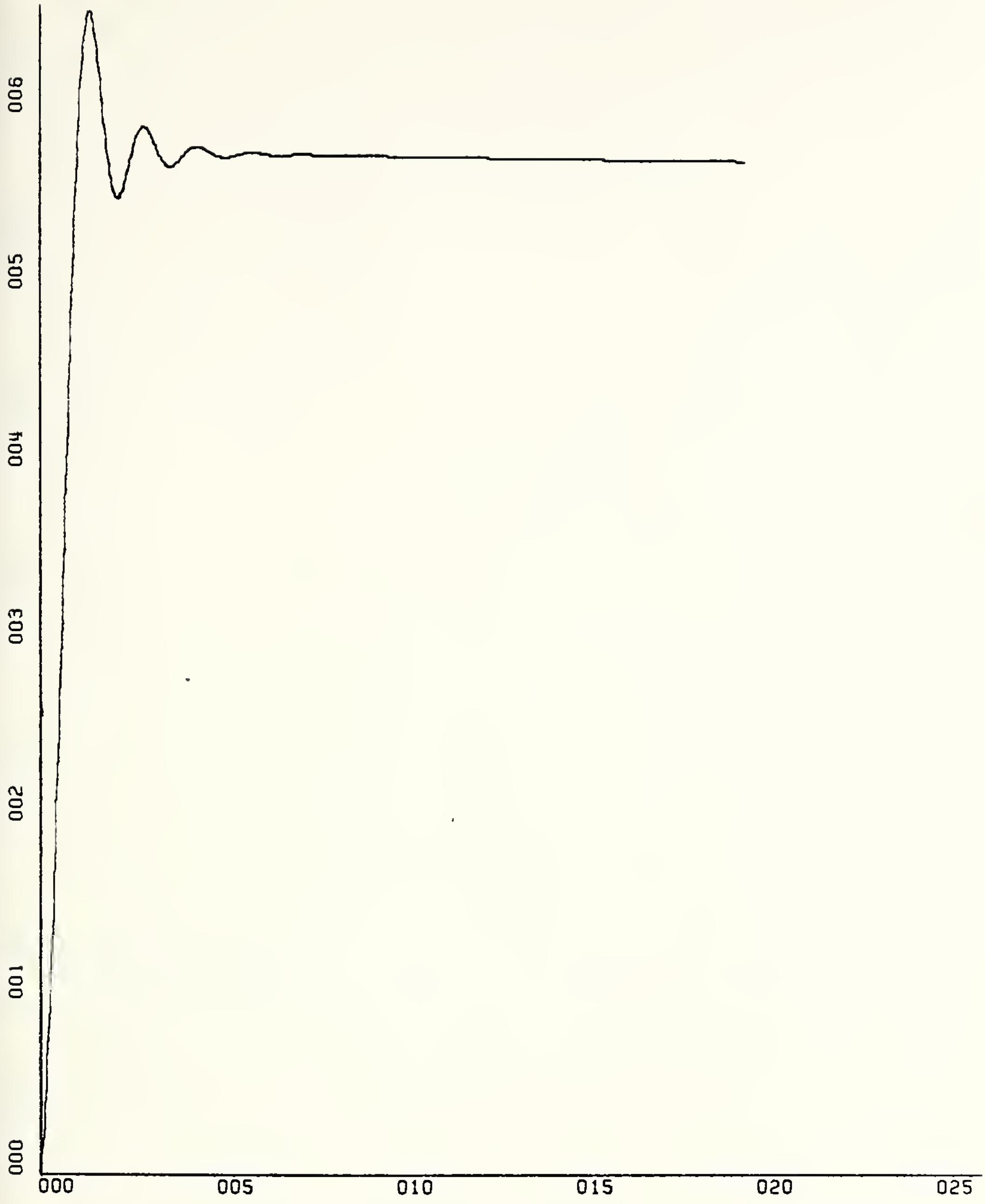


Figure 13. 6 DOF roll angle plot, $\delta_r = 5°$ 30 knot speed



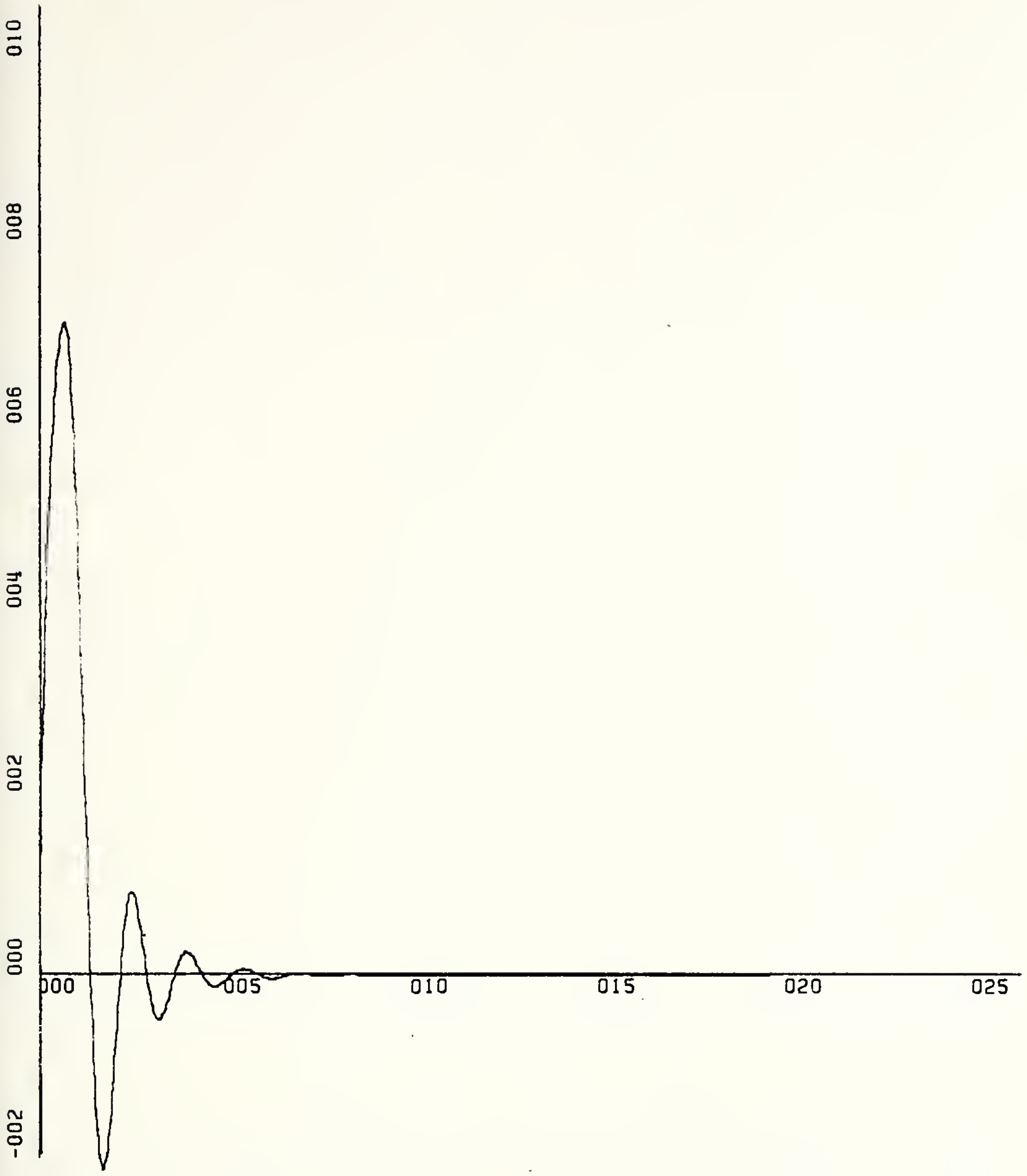
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
XR-3 30 KNØTS SPEED RD=5
PLØT IS RØLL RATE

Figure 14. 6 DOF roll rate plot, $\delta_r = 5°$
30 knot speed



X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
XR-3 20 KNØTS SPEED RD=5
PLØT IS ROLL ANGLE

Figure 15. 6 DOF roll angle plot, $\delta_r = 5°$
20 knot speed



X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E-01 UNITS INCH.
XR-3 20 KNØTS SPEED RD=5
PLØT IS RØLL RATE

Figure 16. 6 DOF roll rate plot, δ_r = 5°
20 knot speed

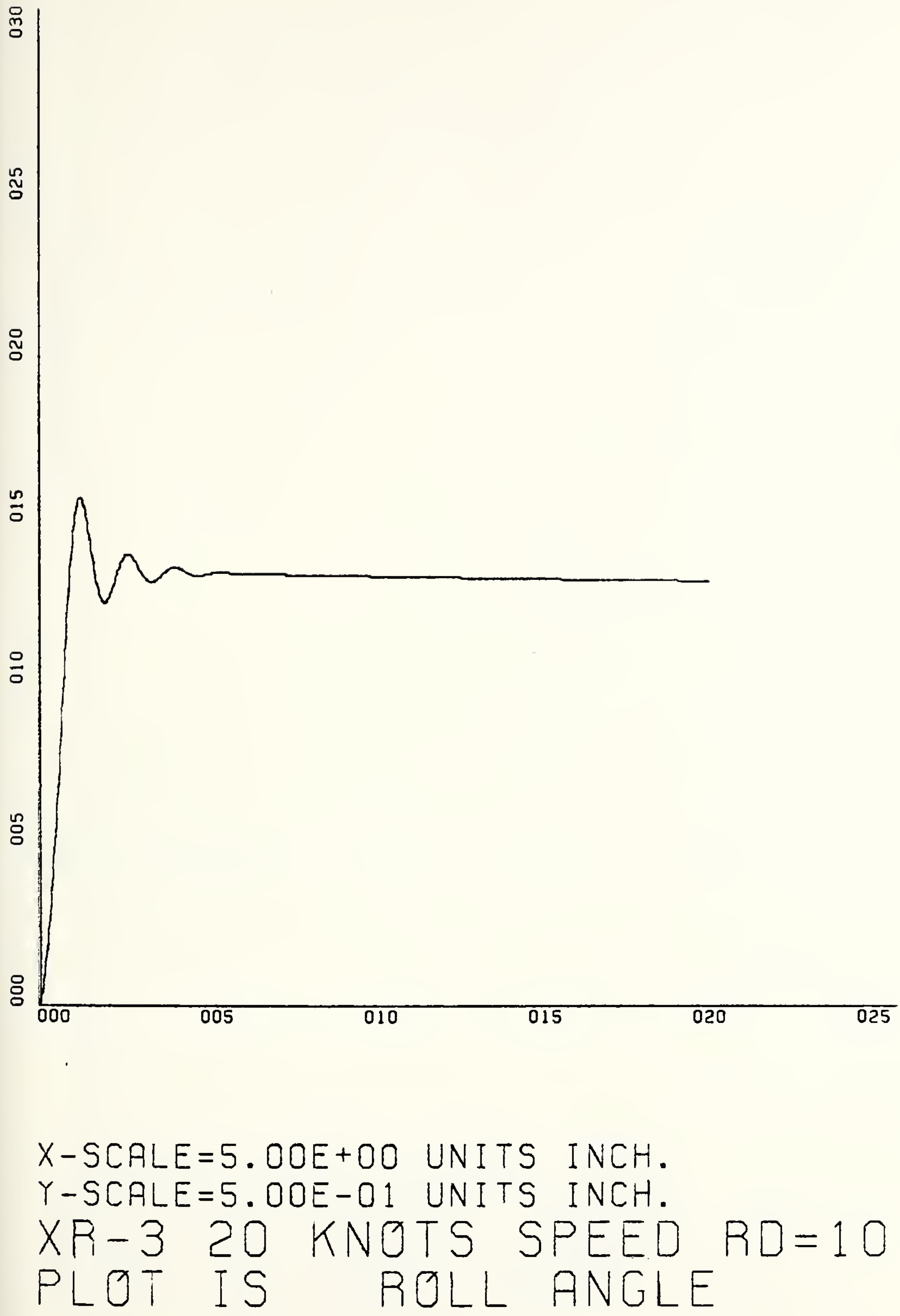


Figure 17. 6 DOF roll angle plot, $\delta_r = 10°$
20 knot speed

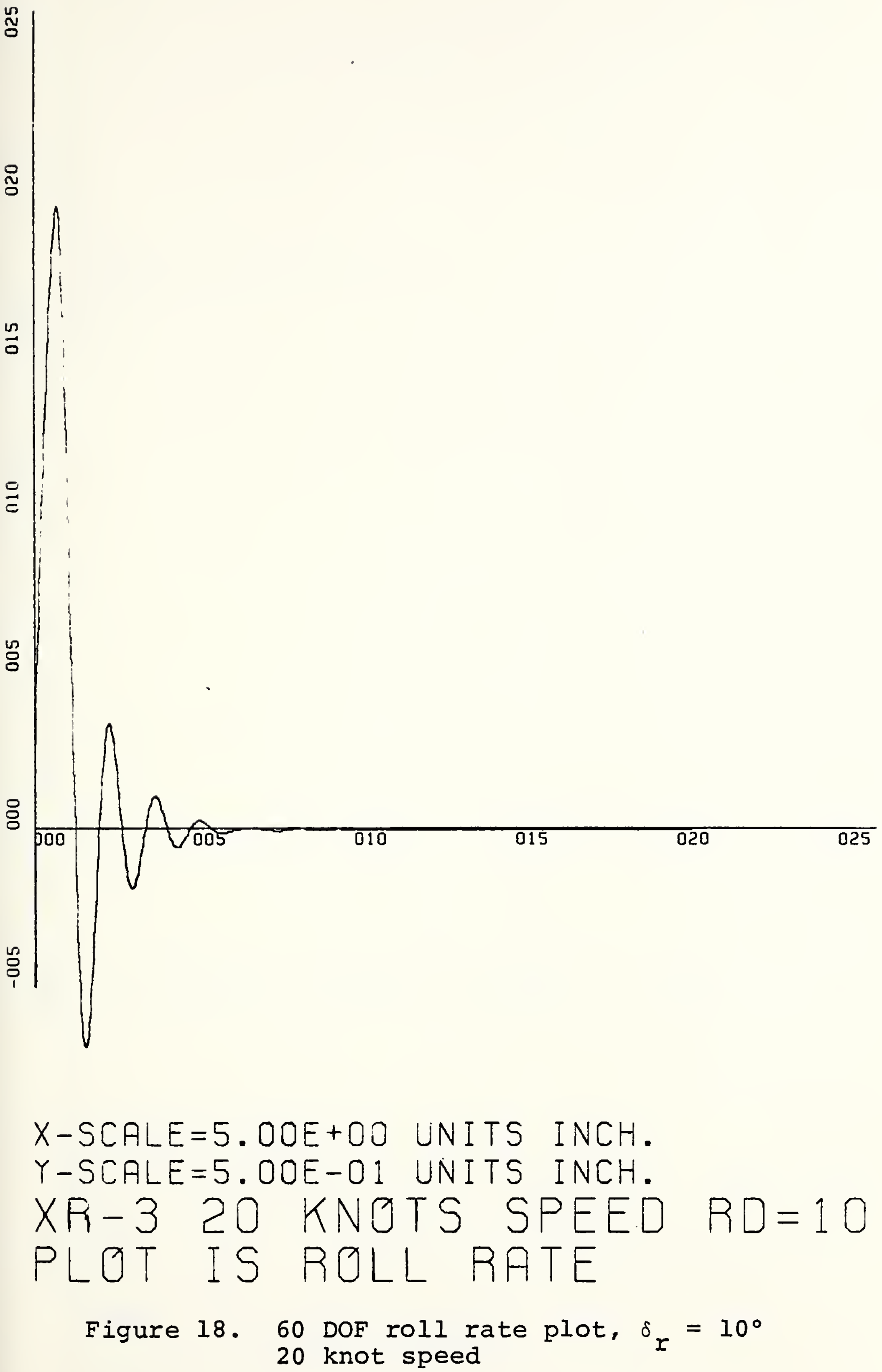


Figure 18. 60 DOF roll rate plot, $\delta_r = 10°$
20 knot speed

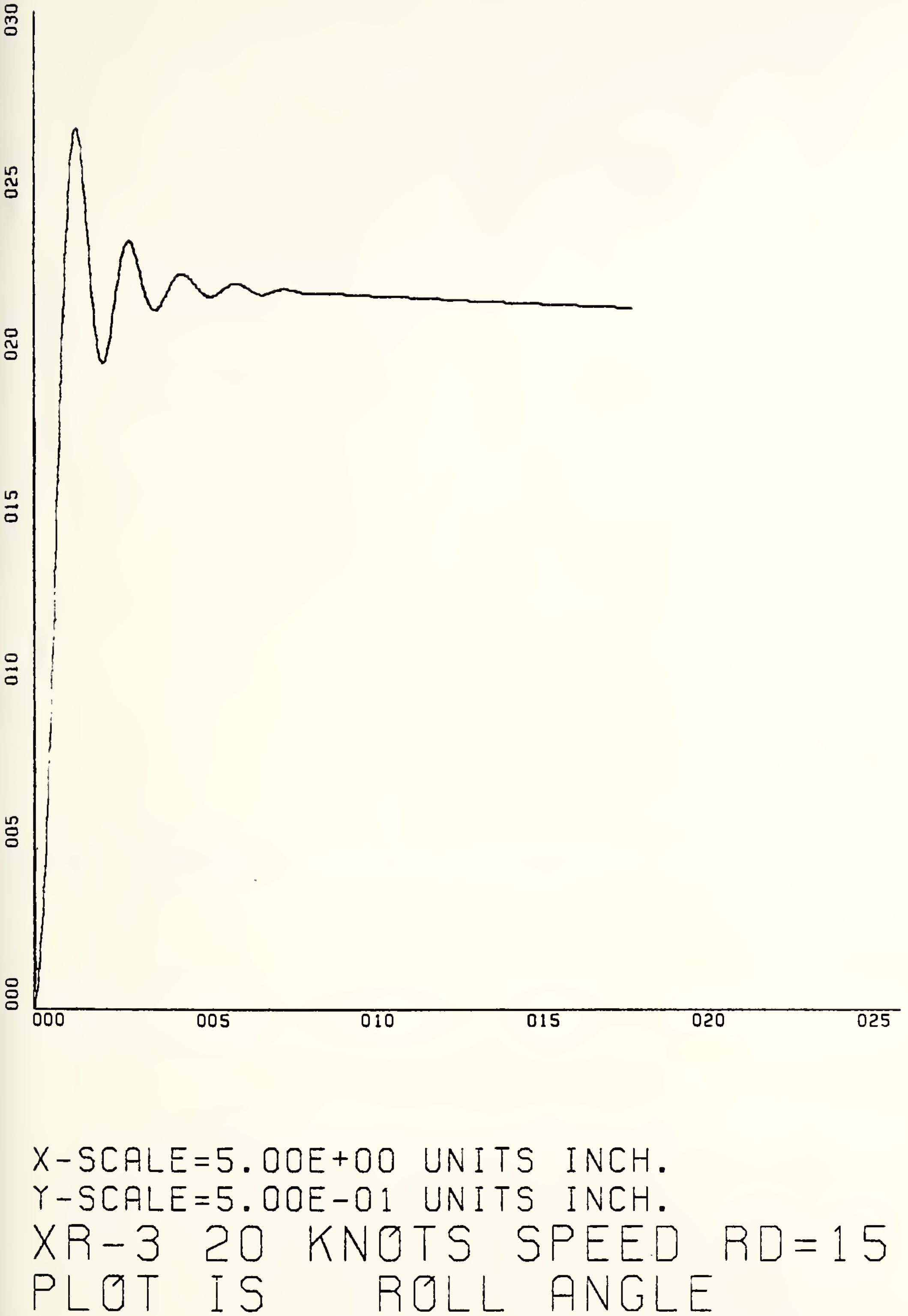
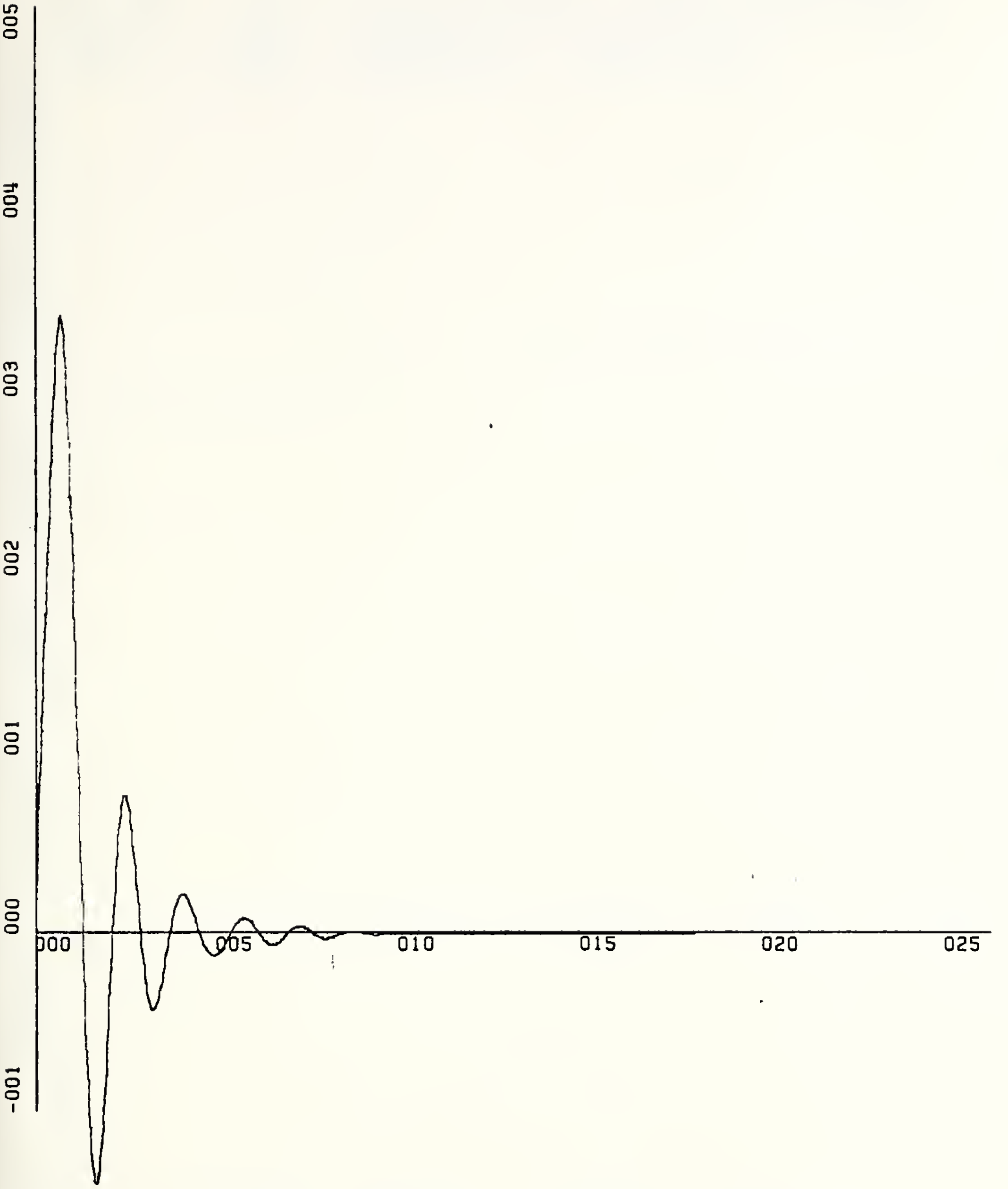


Figure 19. 6 DOF roll angle plot, δ_r = 15°
20 knot speed



X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.
XR-3 20 KNØTS SPEED RD=15
PLØT IS RØLL RATE

Figure 20. 6 DOF roll rate plot; $\delta_r = 15°$
20 knot speed

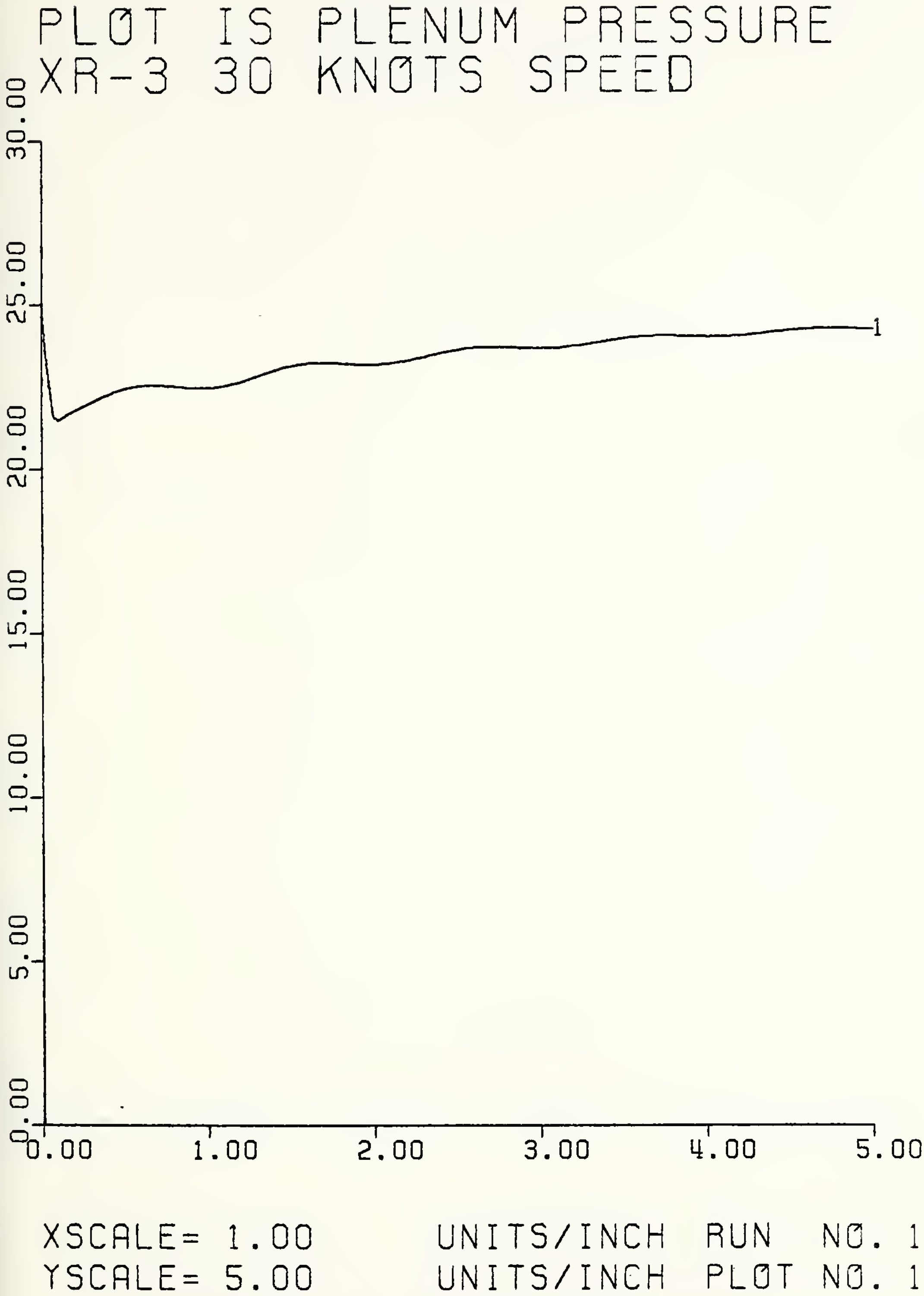


Figure 21. Linear 5 DOF plenum pressure transient

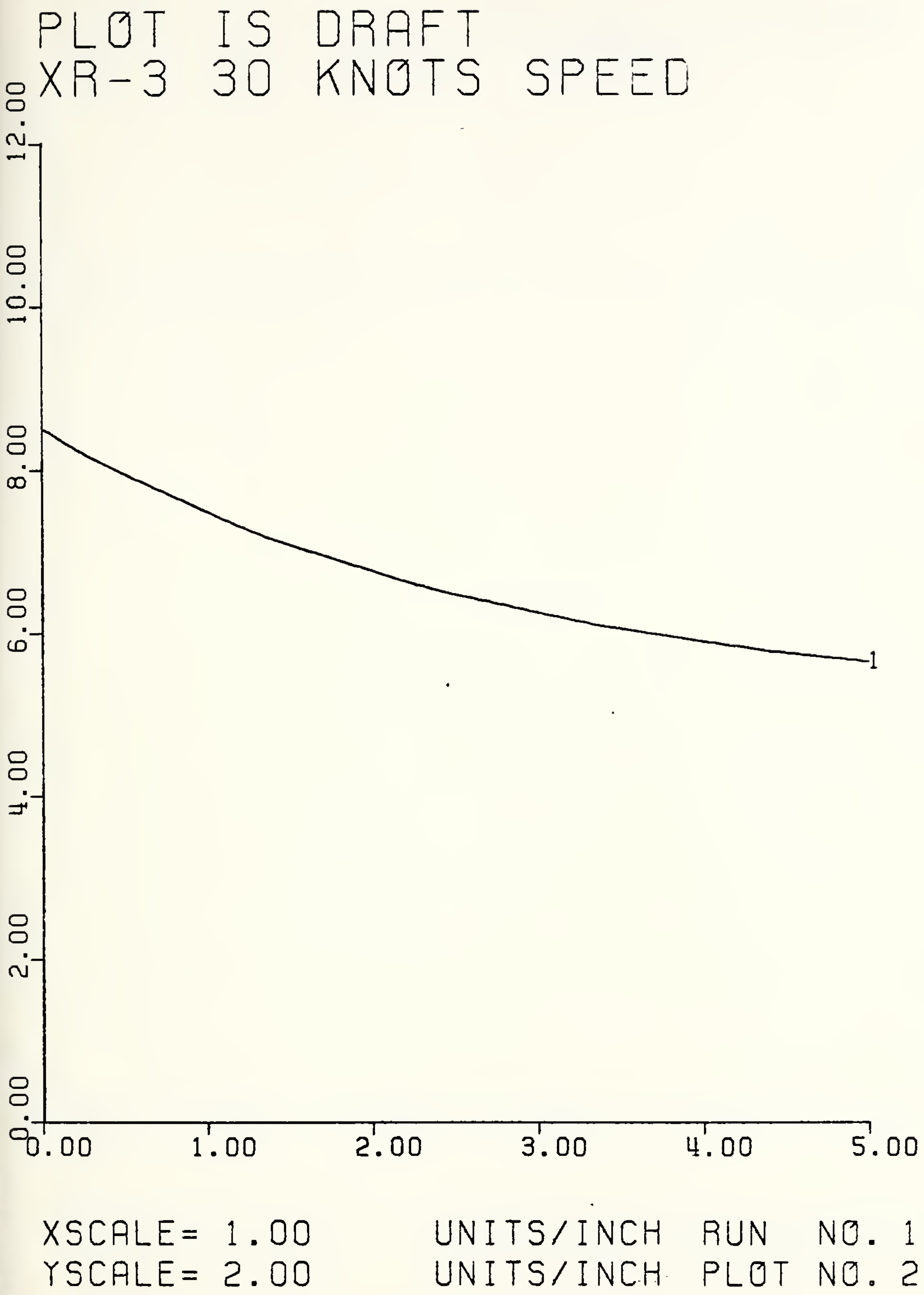


Figure 22. Linear 5 DOF draft transient

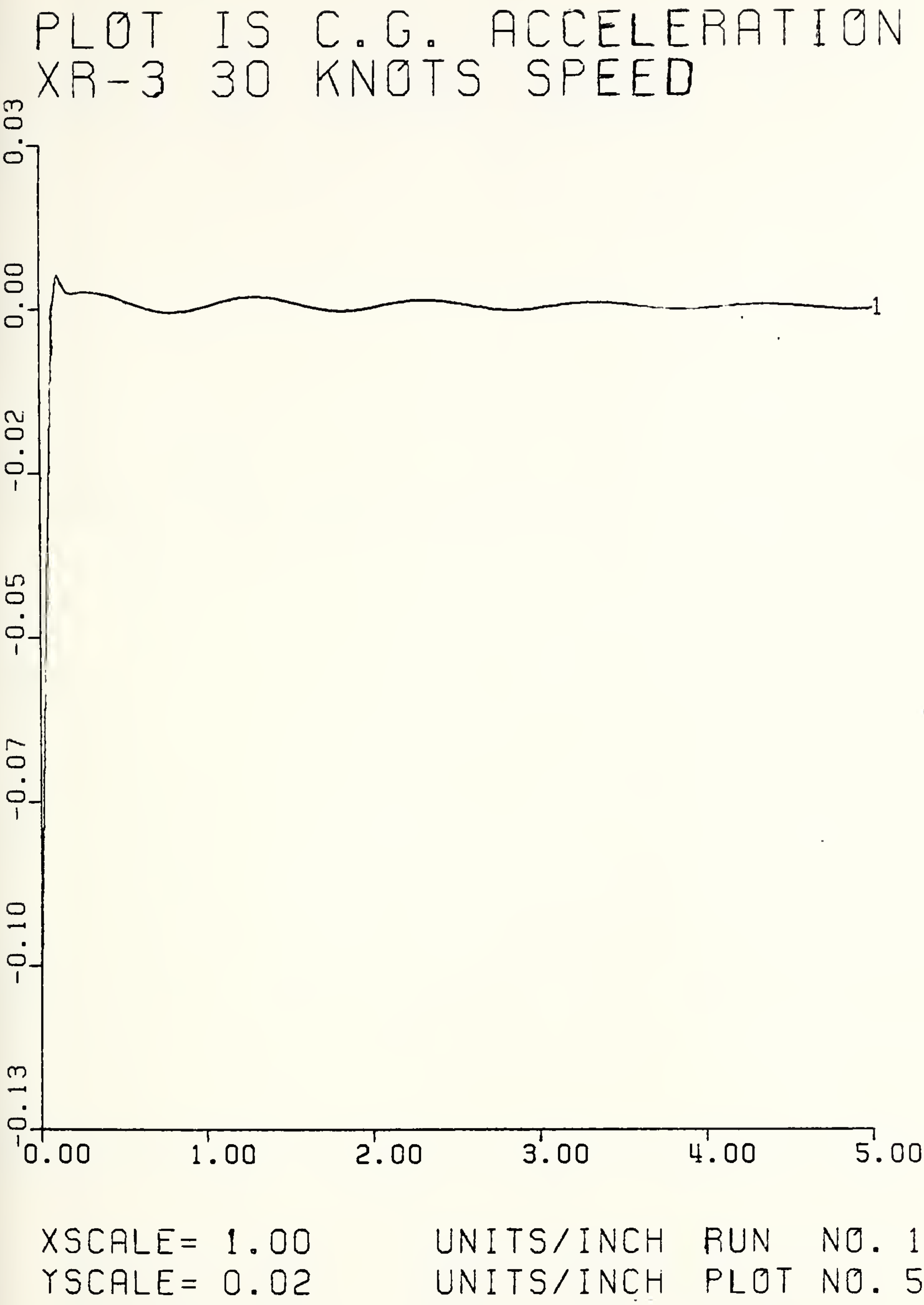


Figure 23. Linear 5 DOF C.G. acceleration

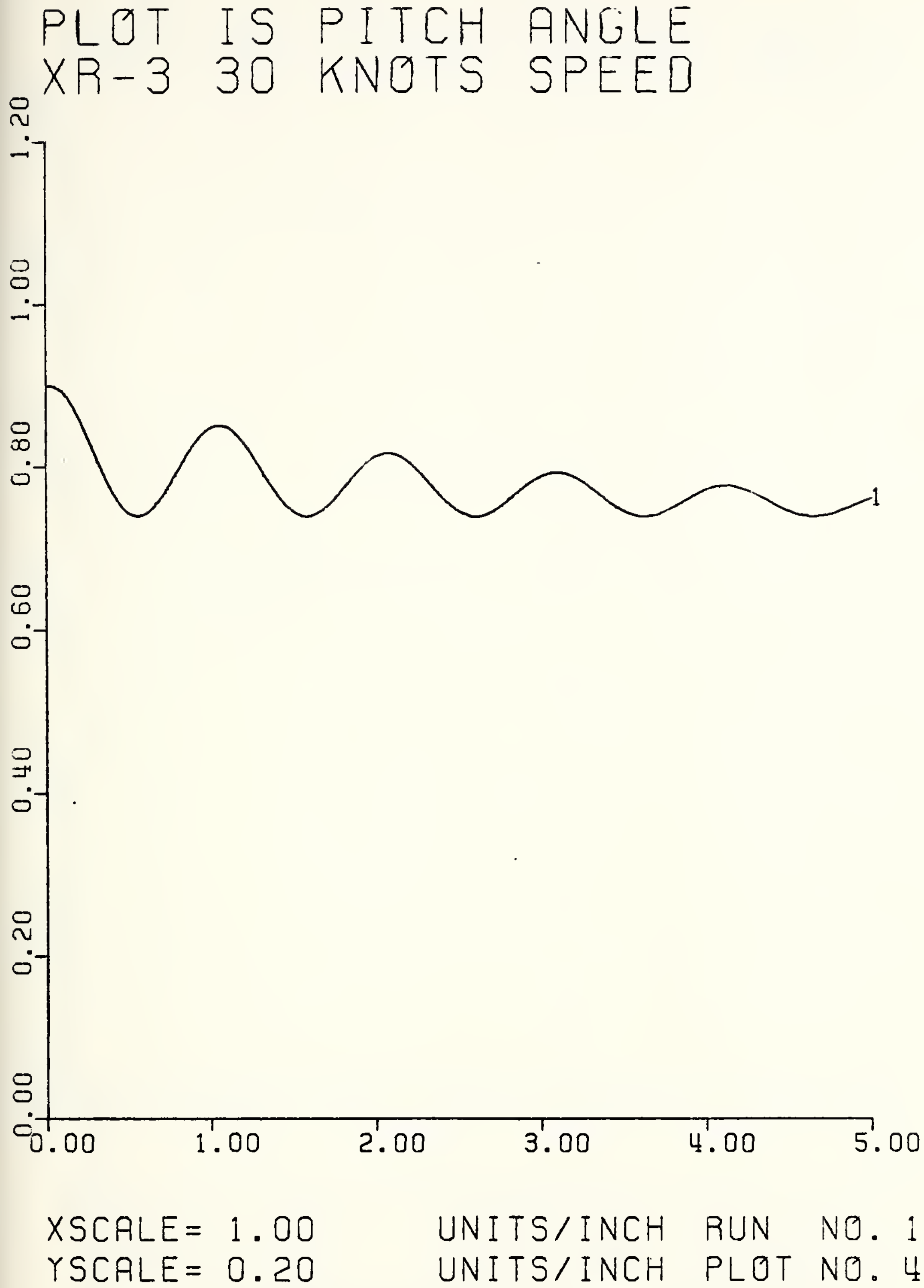


Figure 24. Linear 5 DOF pitch angle transient

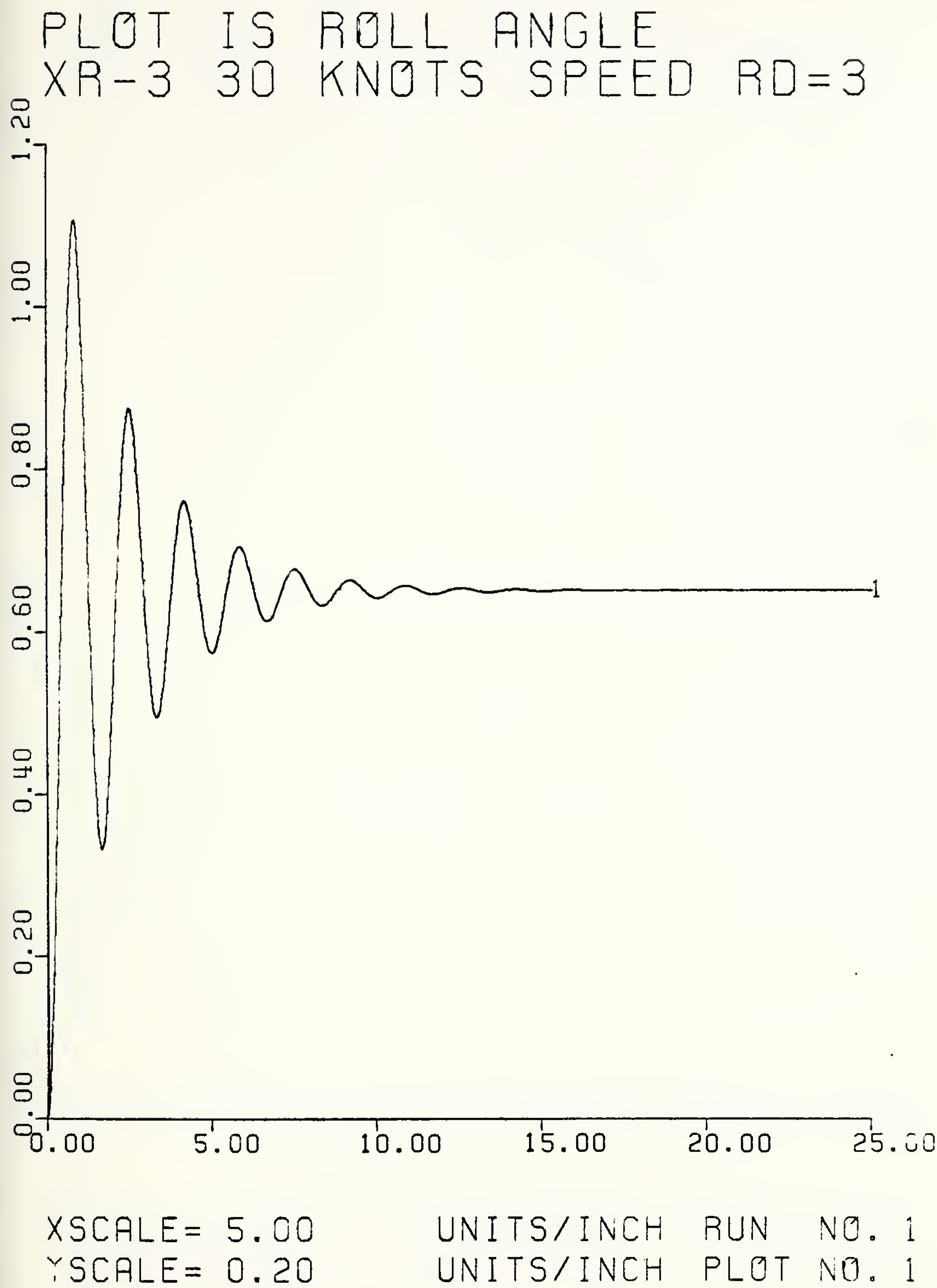


Figure 25. Linear 3 DOF roll angle plot, $\delta_r = 3°$
30 knot speed

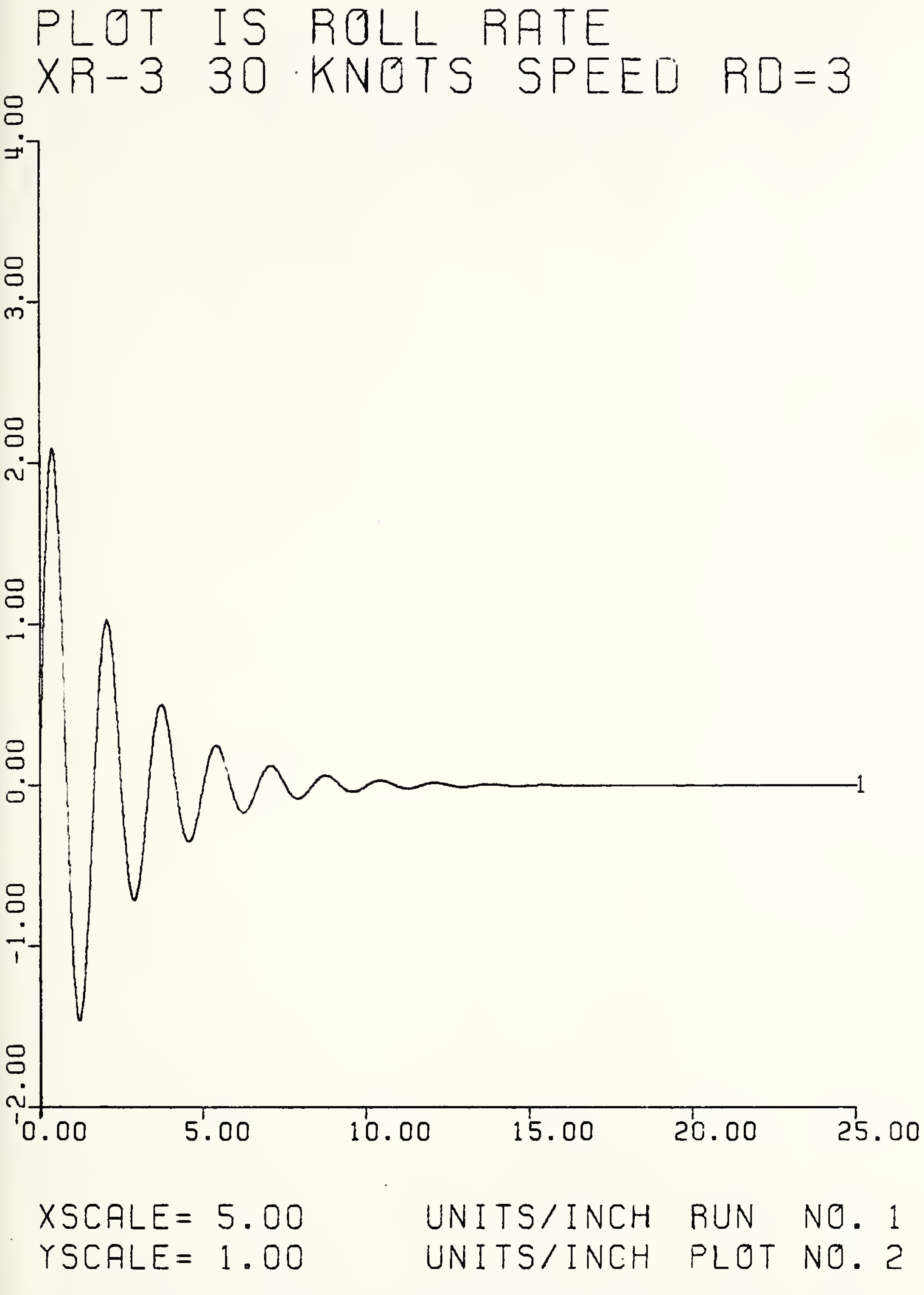


Figure 26. Linear 3 DOF roll rate plot, $\delta_r = 3°$
30 knot speed

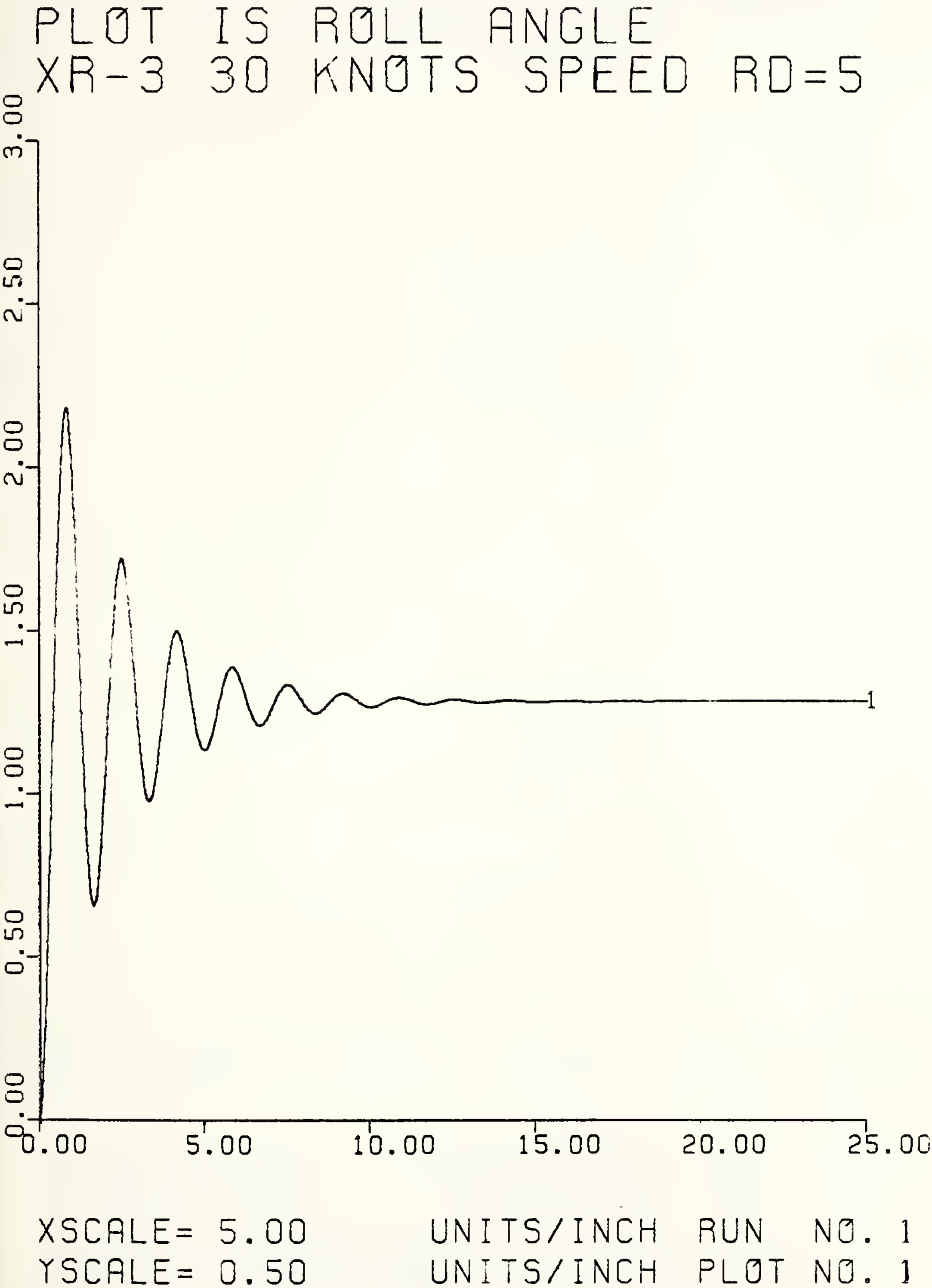


Figure 27. Linear 3 DOF roll angle plot, $\delta_r = 5°$
30 knot speed

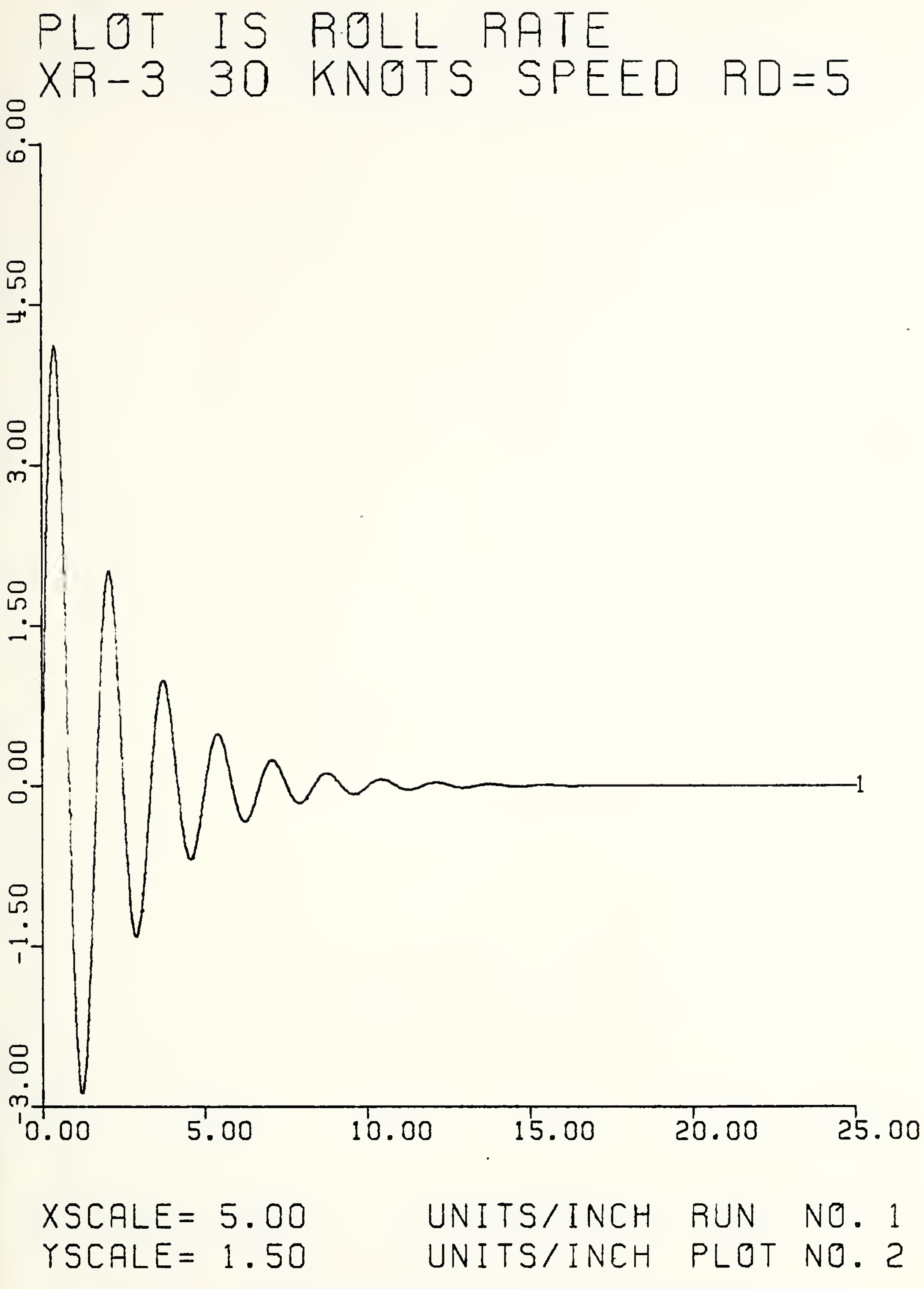


Figure 28. Linear 3 DOF roll rate plot, $\delta_r = 5°$
30 knot speed

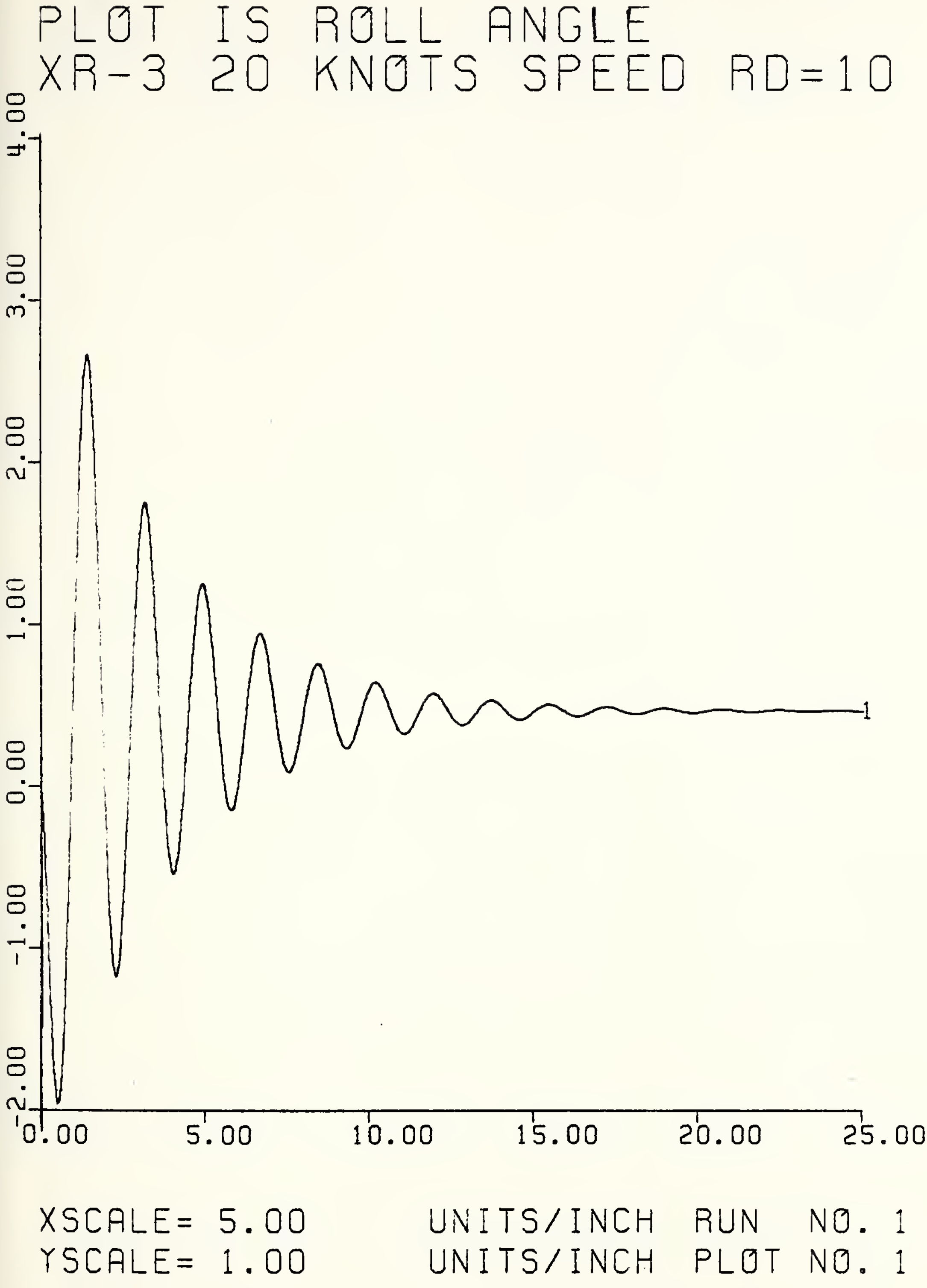


Figure 29. Linear 5 DOF roll angle plot, $\delta_r = 10°$ 20 knot speed (omitting I_{xz} term)

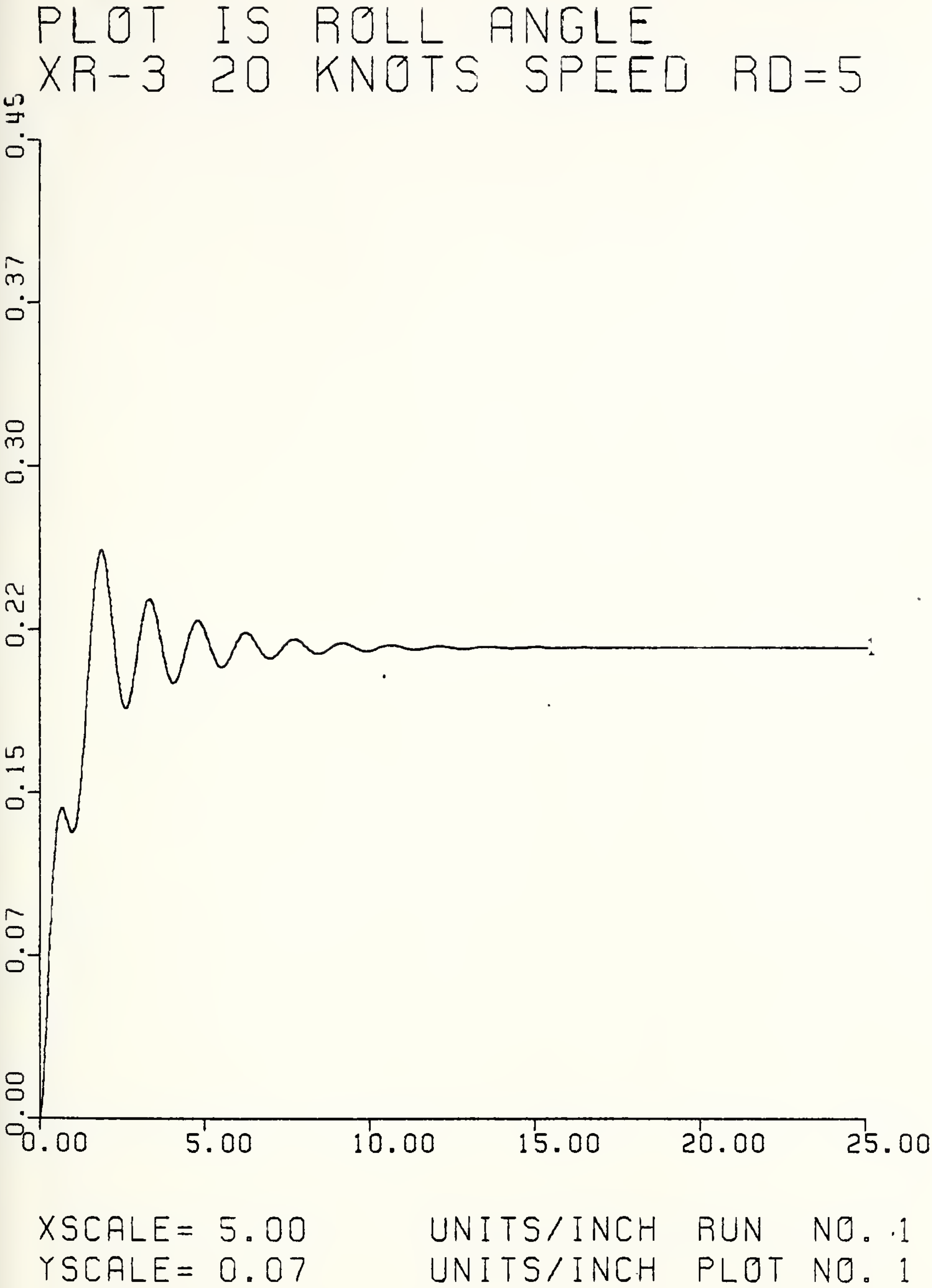


Figure 30. Linear 5 DOF roll angle plot, $\delta_r = 5°$
20 knot speed

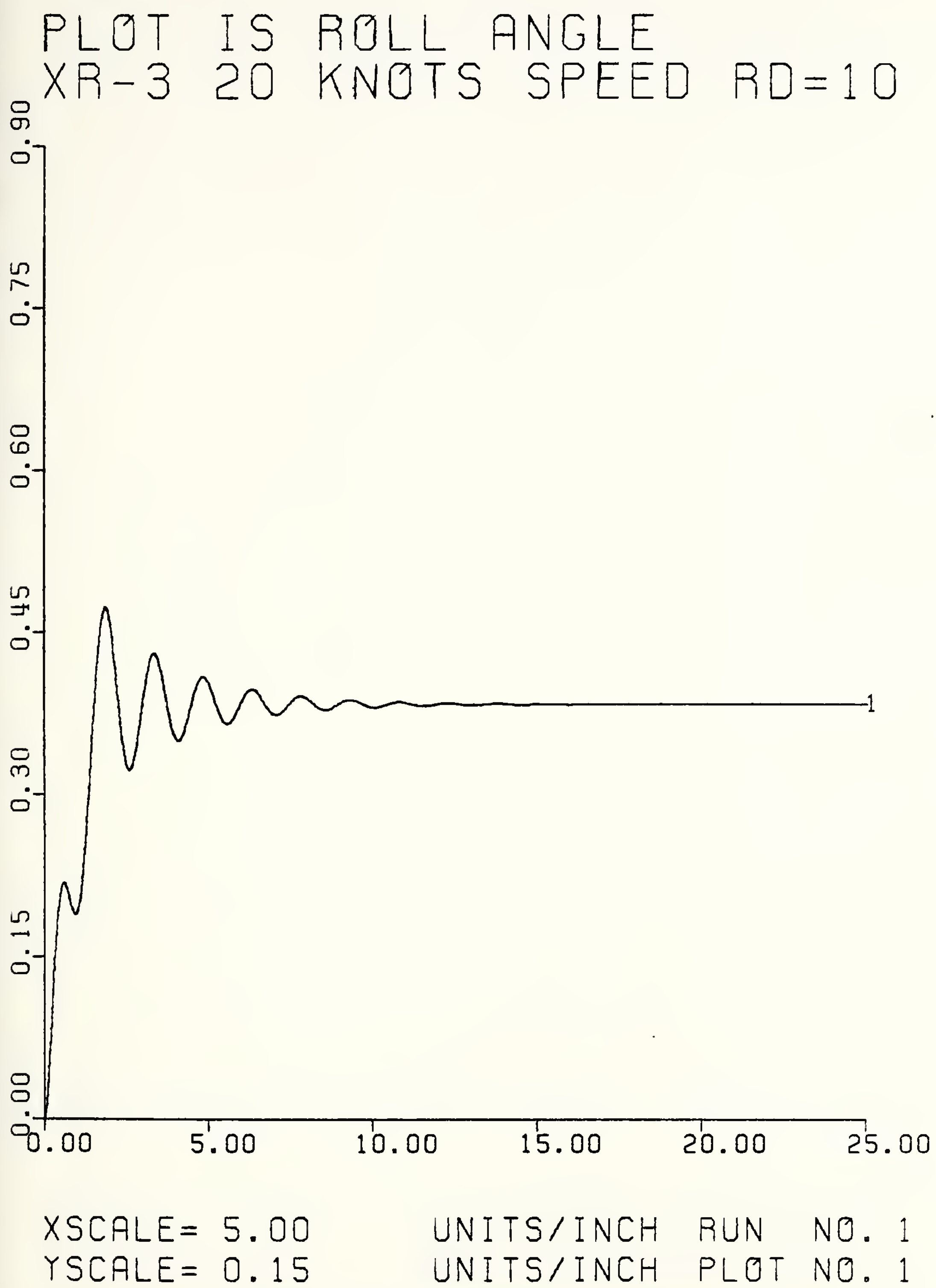


Figure 31. Linear 5 DOF roll angle plot, $\delta_r = 10°$
20 knot speed

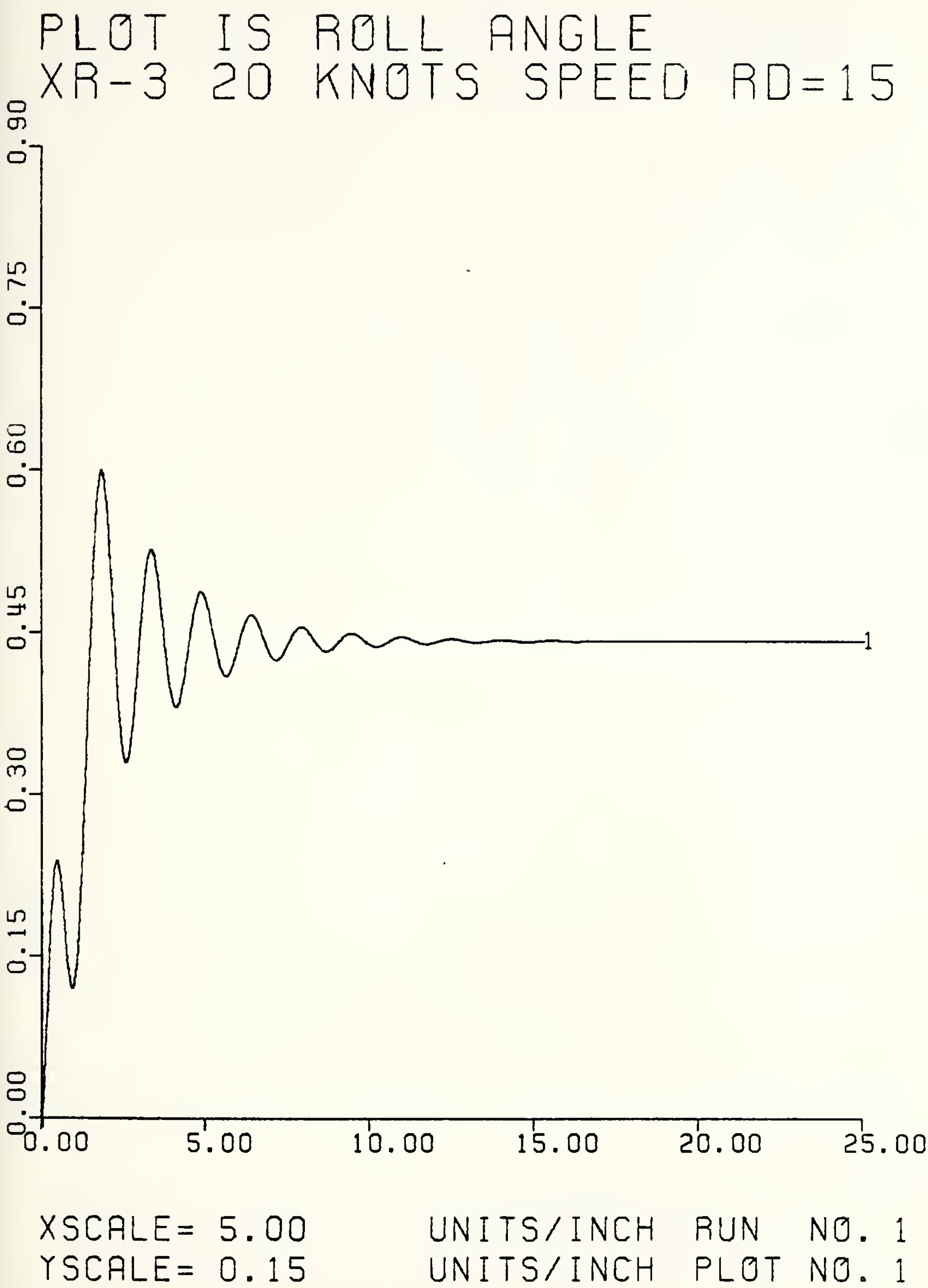


Figure 32. Linear 5 DOF roll angle plot, δ_r = 15°
20 knot speed

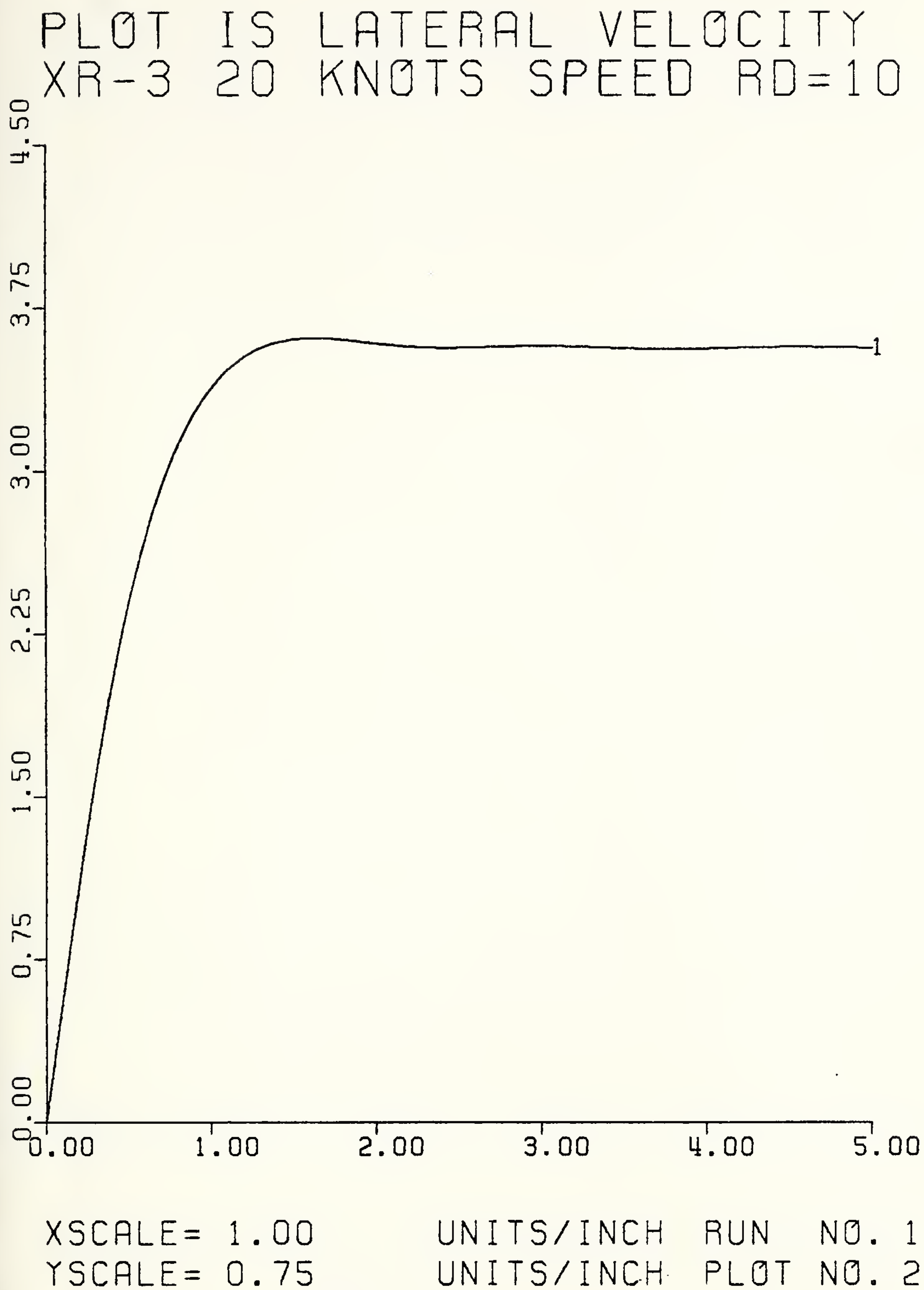


Figure 33. Linear 5 DOF lateral velocity plot

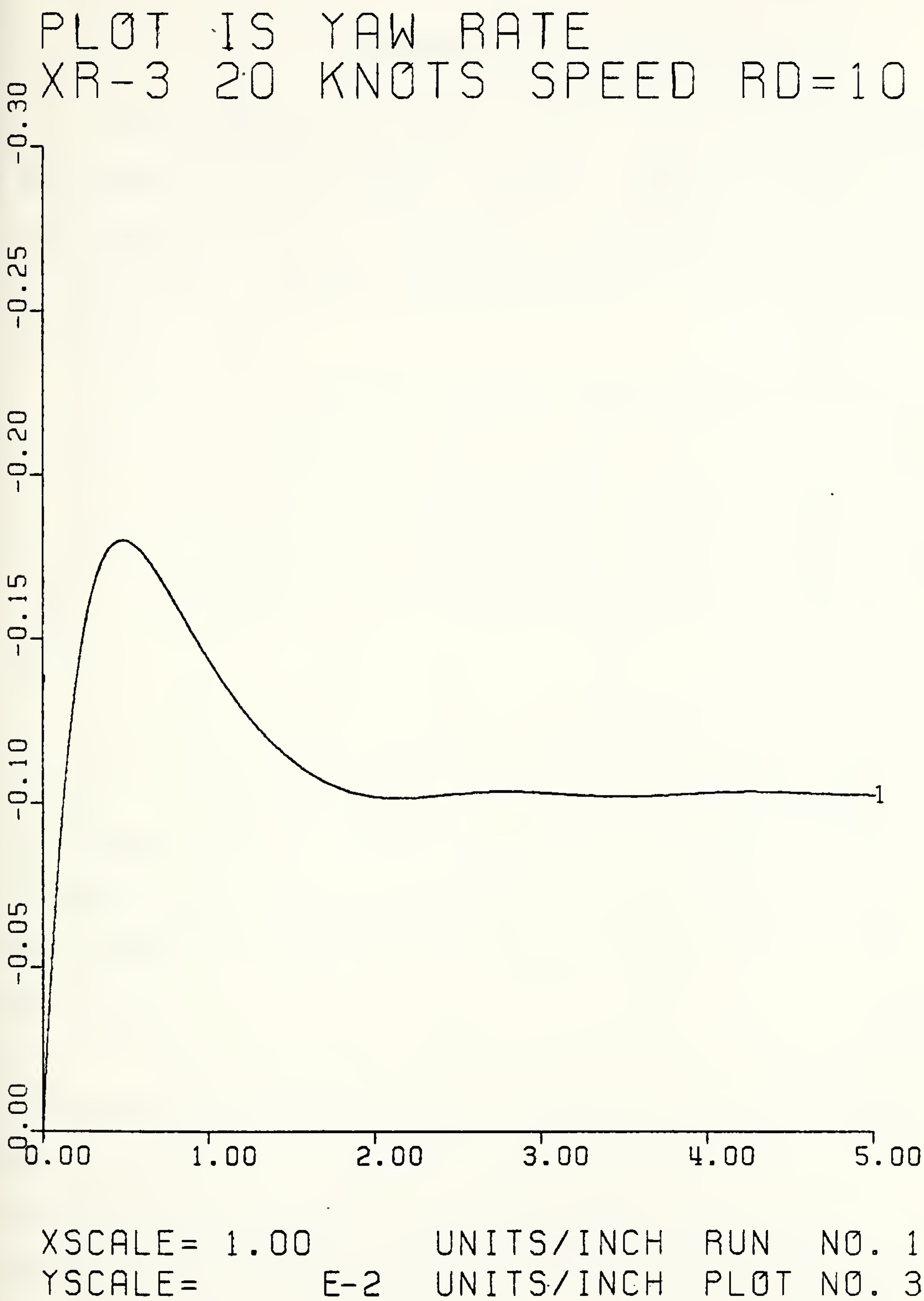


Figure 34. Linear 5 DOF yaw rate plot

VII. CONCLUSIONS AND RECOMMENDATIONS

In the preceding sections, the 5 DOF linear XR-3 model was developed, then weight removal response and roll behavior are compared with 6 DOF nonlinear simulations. Also some of the craft sensitivity parameters are investigated for the XR-3 test craft.

The results of this study are summarized and recommendations are made as follows.

1. The system response is investigated by both a linear model and a 6 DOF nonlinear model by means of sudden weight removal from the C.G. and by sway force disturbance in a turn.

Comparison of results shows that the difference is within 10% for both models. In fact, assuming accuracy in measurements of about 10%, the linearized model gives acceptable results as compared with the nonlinear model. Obviously the linear model simulations take less computer CPU time.

2. Concerning roll response during the turn maneuver, the product inertia term (I_{xz}) affects transient response such as overshoot, damping, etc. More overshoot and oscillatory response have been observed without I_{xz}. However, this term is found to be -2800. from the 6 DOF program. It is suggested that this number be verified.

3. The importance of deadrise is observed for roll steady state behavior. The XR-3 test craft steady state roll angle depends upon the average deadrise angle of the sidewall. Different average deadrise angles have been simulated by means of the linear model and it is observed that the craft rolls inboard or outboard according to the sidewall deadrise configuration.

The 6 DOF nonlinear model SIDEWALL SUBROUTINE must be modified by including a cross flow drag component deadrise projection (lift force). However a new drag coefficient is needed for this lift component.

4. The aerodynamic effect of the craft contributes about 5% of the total yaw moment.

5. The XR-3 failure mode operation (such as fan failure) can be simulated by using either the linear or nonlinear model. But, the nonlinear model is preferable for failure mode simulations, since it includes sidewall and stern seal leakage configurations.

APPENDIX A. COMPUTER PROGRAM LISTING

```
*          XR-3   5 D.O.F.   LINEAR   MODEL
*
*
INTEG RKSFX
INCON A=0.0
INTGER NPLOT
CONST NPLOT=1
INITIAL
*
*      PHYSICAL CONSTANTS
*
       G=32.2                                                      SES00120
       GAMMA=1.4                                                   SES00130
       PA=2116.0                                                   SES00140
       PI=3.141593                                                 SES00150
       RHO=2.0                                                     SES00160
       RHOA=0.002378                                               SES00170
*
*      CRAFT DIMENSIONS
*
       ZS=2.5                                                      SES00440
       BUBHGT=1.915                                                SES00420
       XCPC=0.4634
       XS=10.05
       YSW=5.
       ZSW=2.3
       PLARM=4.23
       PLAREA=6.78
       PLCOEF=0.16
       CDSW=1.28
       DR=70.
       L=20.
       WIDTH=10.0                                                  SES00210
       AL1=10.3                                                    SES00220
       AL2=9.96                                                    SES00230
       AL3=11.2                                                    SES00240
       AL4=8.26                                                    SES00250
       AL5=AL1/2.0                                                 SES00260
       AL6=AL2/2.0                                                 SES00270
       AL7=4.227                                                   SES00280
       AL8=17.1                                                    SES00290
       DR1=61.0                                                    SES00300
       DR2=68.5                                                    SES00310
       WS10=0.2                                                    SES00320
       WS20=0.52                                                   SES00330
       CN=0.9                                                      SES00340
       ALPR=15.72                                                  SES00350
       ALPWL=19.65                                                 SES00360
```

```
      ALDIFF=ALPWL-ALPR                                                 SES00370
      ABDIFF=ALDIFF*WIDTH                                               SES00380
      ABW=ALPWL*WIDTH                                                   SES00400
      ABR=ALPR*WIDTH                                                    SES00410
      VN=((ALPR+ALPWL)/2.0)*BUBHGT*WIDTH                                SES00430
      CIO=35.0                                                          SES00450
      EN=5.0                                                            SES00460
      AIYY=9320.
      AIXX=2870.
      IR=7848.3
      I=-8044.5
      IK=2129.
      A33S=0.7088
*
*     ANGULAR CONVERSION FACTORS AND CONVERSIONS
*
      RADEG=360.0/(2.0*PI)                                              SES00530
      DEGRAD=(2.0*PI)/360.0                                             SES00540
      DR1=DR1*DEGRAD                                                    SES00550
      DR2=DR2*DEGRAD                                                    SES00560
      BETA=DR*DEGRAD
      DR=BETA
*
*     INPUT FINAL OPERATING POINT
*
      V=33.73
      PBBAR=24.8
      THETA=0.26
      ALD=5.34
      VL=3.6
      R=-0.1
      PHI=0.47
      PHD=0.0
      W=6722.
      WF=6050.
*
*     RUDDER ORDER INPUT
*
      RUDANG=10.
*
*     VELOCITY REDUCTION
      V=SQRT(V**2-VL**2)
*
      AMASS=WF/G                                                        SES01480
    5 ALD=ALD/12.0                                                      SES00820
      THETA=THETA*DEGRAD                                                SES00830
      RUDANG=RUDANG*DEGRAD
*
```

```
***      INPUT INITIAL OPERATING POINT
         PH1=0.0
         TH1=0.9
         PB1=24.8
         LD1=8.5
         FYP=186.
         PHI=PHI*DEGRAD
***      CALCULATE INTERMEDIATE VARIABLES AND CONVERSIONS
         ALD1=ALD-AL5*THETA                                        SES00850
         ALD2=ALD+AL6*THETA                                        SES00860
         WS1=WS10+(ALD1/(2.*TAN(DR1)))
         WS2=WS20+(ALD2/(2.*TAN(DR2)))
         AK1=2.0*RHO*G*AL1                                         SES00890
         AK2=2.0*RHO*G*AL2                                         SES00900
         AK3=WIDTH/(SIN(31*DEGRAD))                                SES00910
         AK4=WIDTH/(SIN(32*DEGRAD))                                SES00920
         XSEAL1=(ALD-AL3*THETA)/SIN(31.0*DEGRAD)                   SES00930
         XSEAL2=(ALD+AL4*THETA)/SIN(32.0*DEGRAD)                   SES00940
         ASEAL1=WIDTH*XSEAL1                                       SES00950
         ASEAL2=WIDTH*XSEAL2                                       SES00960
         PLC=RHO*PLAREA*V**2*PI*PLCOEF
         XCPO=ALFWL/2.0-(119.6/12.0)                               SES00390
         XCP=XCPO+(ALDIFF*ALD/BUBHGT)/2.0+XCPC                     SES00990
         AB=(ABW-(ABW-ABR)*(ALD/BUBHGT))/COS(PHI)
         AB1=AB*COS(PHI)
         VB=VN-AB1*ALD
         PB=PA+PBBAR                                               SES01020
         AMB=RHOA*VB*(PB/PA)**(1.0/GAMMA)
         QIN=EN*(QIO-PBBAR)                                        SES01040
         AL=QIN/(CN*SQRT(2.0*PBBAR/RHOA))                          SES01050
         BC2=PI/8.*RHO*(AL1+AL2)*ALD**2*(COTAN(BETA))**2
         DSS=ALD+XS*THETA
         DSS1=ALD+YSW*PHI+XS*THETA
         DSS2=ALD-YSW*PHI+XS*THETA
         BL2=(WS20+WIDTH)/2.+ALD2/(2.*TAN(DR2))
         BL1=(WS10+WIDTH)/2.+ALD1/(2.*TAN(DR1))
         BW1=ALD1/TAN(DR1)+WS10
         BW2=ALD2/TAN(DR2)+WS20
         BS=WS20+(ALD+XS*THETA)/TAN(DR2)
         A22S=(RHO*0.2*PI*(DSS1**2+DSS2**2)/2.)
         D1=0.5*RHO*CDSW*L
         D2=2.*A33S*YSW**2*V
         D3=A22S*V
         VREL=VL-XS*R-(ZS-ALD/2.)*PHD
```

```
*
*     CUTPUT FCRCES,MOMENTS, AND RESIDUALS AT FINAL OPER POINT
*
      HPRES=-AB*PBBAR
      PPRES=-HPRES*XCP
      HBF=-AK1*ALD1*WS1                                                 SES01140
      HBA=-AK2*ALD2*WS2                                                 SES01150
      HSF=-PBBAR*ASEAL1                                                 SES01160
      HSA=-(PBBAR+2.0)*ASEAL2                                           SES01170
      HPF=-PLC*THETA
      HPA=-PLC*THETA
      PBF=-AL5*HBF                                                      SES01230
      PBA=AL6*HBA                                                       SES01240
      PLSF=AL3-XSEAL1/2.0                                               SES01260
      PLSA=AL4+XSEAL2/2.0                                               SES01270
      PSF=-HSF*PLSF                                                     SES01280
      PPLAN=-2.*PLC*PLARM*THETA
      PSA=HSA*PLSA                                                      SES01290
      RPRES=-HPRES*(ZS-ALD)*PHI
      RBF=-AK1*BL1**2*BW1*PHI
      RBA=-AK2*BL2**2*BW2*PHI
      RSF=-(WIDTH/2.52)**3*XSEAL1*RHO*G*PHI
      RSA=-(WIDTH/2.52)**3*XSEAL2*RHO*G*PHI
      RES1=W+HBF+HBA+HSF+HSA+HPF+HPA+HPRES                              SES01310
      RES2=PBF+PBA+PSF+PSA+PPLAN+PPRES                                  SES01320
      RES3=RPRES+RBF+RBA+RSF+RSA
      ACCEL=RES1/AMASS                                                  SES01330
      PACCEL=RES2/AIYY                                                  SES01340
      RACCEL=RES3/AIXX
      WSTEP=WF-W
*
      SIN31=SIN(31.0*DEGRAD)                                            SES01750
      SIN32=SIN(32.0*DEGRAD)                                            SES01760
*
*
*     COMPUTE SENSITIVITY COEFFICIENTS
*
*
*     DERIVATIVES OF PBBAR AND MB
*
      DPBDZ=GAMMA*(AB1-ABDIFF*ALD/BUBHGT)*PB/VB
      DPBMB=GAMMA*PB/AMB                                                SES01810
      DMBPB=-RHOA*(EN+CN*AL/(RHOA*SQRT(2.0*PBBAR/RHOA)))                SES01820
      DMBZ=DMBPB*DPBDZ                                                  SES01830
      DMBME=DMBPB*DPBMB                                                 SES01840
*
*     DERIVATIVES OF HEAVE FORCES W/RESPECT TO Z
*
```

```
      DHBFZ=-AK1*((ALD-AL5*THETA)/TAN(DR1)+WS10)                        SES01880
      DHBAZ=-AK2*((ALD+AL6*THETA)/TAN(DR2)+WS20)                        SES0189C
      DHBZ=(DHBFZ+DHBAZ)                                                SES01900
      DHSFZ=-AK3*PBBAR-AK3*(ALD-AL3*THETA)*DPBDZ                        SES01910
      DPBZ=PBBAR*ABDIFF/BUBHGT
      DHSAZ=-AK4*(PBBAR+2.)-AK4*(ALD+AL4*THETA)*DPBDZ                   SES01920
      DHSZ=DHSFZ+DHSAZ                                                  SES01930
      DHPBZ=-AB*DPBDZ+DPBZ
      DZZ=(DHBZ+DHSZ+DHPBZ)/AMASS
*
*     DERIVATIVES OF HEAVE FORCES W/RESPECT TO THETA
*
      DHBFTH=AK1*(AL5*(ALD-AL5*THETA)/TAN(DR1)+AL5*WS10)
      DHBATH=-AK2*(AL6*(ALD+AL6*THETA)/TAN(DR2)+AL6*WS20)
      DHSFTH=AK3*AL3*PBBAR                                              SES02010
      DHSATH=-AK4*AL4*(PBBAR+2.0)                                       SES02020
      DSWTH=-2.*V**2*(A33S+THETA*(2.*RHO*PI*BS*XS/TAN(DR2))/8.)
      DHPFTH=-FLC+0.5*DSWTH
      DHPATH=-FLC+0.5*DSWTH
      DHBTH=DHBFTH+DHBATH                                               SES02050
      DHSTH=DHSFTH+DHSATH                                               SES02060
      DHPTH=DHPFTH+DHPATH
      DZTH=(DHBTH+DHSTH+DHPTH)/AMASS                                    SES02080
*
*     DERIVATIVE OF HEAVE FORCE W/RESPECT TO MB
*
      DHPBMB=-AB*DPBMB                                                  SES02120
      DHSFMB=-ASEAL1*DPBMB                                              SES02130
      DHSAMB=-ASEAL2*DPBMB                                              SES02140
      DZMB=(DHPBMB+DHSFMB+DHSAMB)/AMASS                                 SES02150
*
      DPDP=-2.*(BC2+A33S*XS)*V
      DZDP=DPDP/AMASS
*
*      DERIVATIVES OF HEAVE FORCES W/R TO PHI
*
      DZPH=0.0
*
*     DERIVATIVES OF PITCH MOMENTS W/RESPECT TO THETA
*
      DPBFTH=-AL5*DHBFTH                                                SES02190
      DPBATH=AL6*DHBATH                                                 SES02200
      DPBTH=DPBFTH+DPBATH                                               SES02210
      DPPLTH=-2.*PLC*PLARM+DSWTH*XS
      DPSFTH=-PBBAR*(PLSF*AL3*WIDTH/SIN31-ASEAL1*AL3/(2.*SIN31))
      DPSATH=-(PBBAR+2.)*(PLSF*AL4*WIDTH/SIN32+ASEAL2*AL4/(2.*SIN32))
      DPPRTH=0.0
      DPSTH=(DPSFTH+DPSATH)                                             SES02250
```

```
      DTHTH=(CPBTH+DPPLTH+DPSTH+DPPRTH)/AIYY
*
*       DERIVATIVES OF PITCH MCMENTS W/R TO THETADOT
*
      DPDMP=-2.*A33S*XS**2*V
      DTHDTH=CPDMP/AIYY                                                 SES02290
*
*     DERIVATIVES OF PITCH MOMENTS W/RESTECT TO Z
*
      CPBFZ=-AL5*DHBFZ                                                  SES02340
      DPBAZ=AL6*CHBAZ                                                   SES02350
      DPPBZ=XCP*(AB*DPBDZ-PBBAR*ABDIFF/BUBHGT)+AB*PBBAR*ALDIFF/...
     (2.*BUBHGT)
      DPSFZ=PBBAR*(PLSF*WIDTH/SIN31-ASEAL1/(2.0*SIN31))                 SES02370
      DPSAZ=-(PBBAR+2.)*(PLSA*WIDTH/SIN32+ASEAL2/(2.*SIN32))
      DPSFPZ=ASEAL1*PLSF*CPBDZ                                          SES02390
      DPSAPZ=-ASEAL2*PLSA*DPBDZ                                         SES02400
      CPSFZ=CPSFZ+DPSFPZ                                                SES02410
      DPSAZ=CPSAZ+DPSAPZ                                                SES0242C
      DPSZ=(DPSFZ+DPSAZ)                                                SES02430
      CPBZ=CPBFZ+DPBAZ                                                  SES02440
      CPPZ=0.C
      DTHZ=(CPSZ+DPBZ+DPPBZ+DPPZ)/AIYY
*
*     DERIVATIVE OF PITCH MCMENT W/RESPECT TO MB
*
      DPPBMB=AB*XCP*DPBMB
      DPSFMB=-PLSF*DHSFMB                                               SES02500
      DPSAMB=PLSA*DHSAMB                                                SES02510
      DTHMB=(DPPBMB+DPSFMB+DPSAMB)/AIYY                                 SES0252C
*
*     DERIVATIVES OF PITCH MOMENTS W/R TO PHI
*
      DPPH=0.0
*
*
*     RUDDER HIDRODYN.
      RAREA=0.68
      RSPAN=1.21
      XR=-11.175
      ZR=2.7C8
      RASPR=2.15
      CSR=ALC-XR*THETA
      RCLB=2.*PI*RASPR/(RASPR+3.)
      ENDFAC=1.+DSR/(DSR+RSPAN)
      VH=VL+XR*R-ZR*PHD
      QQ=0.5*RHC*V**2*RAREA
      RDC=2.*CC*ENDFAC*RCLB
```

```
      FRD=RDC*RLDANG
      PM=1.0
      IF(VL.LT.0.0) GO TO 10
      PM=-1.
   10 CONTINUE
*
*     DERIVATIVES OF ROLL MOMENTS W/R TO Z
*
      DRSFZ=-(WIDTH/2.28)**3*RHO*G*PHI/SIN31
      DRSAZ=-(WIDTH/2.28)**3*RHO*G*PHI/SIN32
      DRSZ=DRSFZ+DRSAZ
      DRBFZ=-AK1*PHI*(2.*BL1*BW1/(2.*TAN(DR1))+BL1**2/TAN(DR1))
      DRBAZ=-AK2*PHI*(2.*BL2*BW2/(2.*TAN(DR2))+BL2**2/TAN(DR2))
      DRBZ=DRBFZ+DRBAZ
      DRPRZ=-PHI*(AB*PBBAR+(ZS-ALD)*DHPBZ)
      DFYDZ=FM*C1*VREL**2
      DRPLZ=DFYDZ*(COS(DR)*YSW-SIN(DR)*ZSW)
      DRZ=(DRSZ+DRBZ+DRPRZ+DRPLZ)/AIXX
*
*     DERIVATIVES OF ROLL MOMENTS W/R TO THETA
*
      DRSFTH=(WIDTH/2.28)**3*RHO*G*PHI*(AL3/SIN31)
      DRSATH=-(WIDTH/2.28)**3*RHO*G*PHI*(AL4/SIN32)
      DRSTH=DRSFTH+DRSATH
      DRBFTH=AK1*PHI*(2.*BL1*BW1*AL5/(2.*TAN(DR1))+BL1**2*AL5/TAN(DR1))
      DRBATH=-AK2*PHI*(2.*BL2*BW2*AL6/(2.*TAN(DR2))+BL2**2*AL6/TAN(DR2))
      DRBTH=DRBFTH+DRBATH
      DRPTH=0.0
      DRTH=(DRSTH+DRBTH+DRPTH)/AIXX
*
*     DERIVATIVES OF ROLL MOMENTS W/R TO MB
*
      DRPRMB=AE*(ZS-ALD)*PHI*DPBMB
      DRMB=DRPRMB/AIXX
*
*     DERIVATIVES OF ROLL MOMENTS W/R TO PHI
*
      DRSFPH=-(WIDTH/2.28)**3*XSEAL1*RHO*G
      DRSAPH=-(WIDTH/2.28)**3*XSEAL2*RHO*G
      DRSPH=DRSFPH+DRSAPH
      DRBFPH=-AK1*BL1**2*BW1
      DRBAPH=-AK2*BL2**2*BW2
      DRBPH=DRBFPH+DRBAPH
      DRPRPH=PBBAR*(ZS-ALD)*AB1
      DFYDPH=-FM*D1*VREL**2*PM*YSW
      DRPLPH=DFYDPH*(COS(DR)*YSW-SIN(DR)*ZSW)
      DRPH=(DRSPH+DRBPH+DRPRPH+DRPLPH)/AIXX
*
```

```
*     DERIVATIVES OF ROLL MOMENTS W/R TO PHIDOT
*
      DFYPH=A22S*V*ZS
      DRD=ALD-FM*YSW*PHI
      DFYDPD=-FM*D1*DRD*2.*VREL*(ZS-ALD/2.)
      DF=DFYDPD+DFYPH
      DRDPH1=-D2+DF*(COS(DR)*YSW-SIN(DR)*ZSW)-DFYPH*ZS
      DRWAV=-32./PI*YSW**2*BC2
      DRDPHD=DRDPH1+DRWAV
      DRRUPD=-RDC*(ENDFAC/V)*ZR**2
      DRPD=(DRDPHD+DRRUPD)/AIXX
*
*     ROLL MOMENTS W/R TO YDOT
*
      DFYDYD=FM*D1*DRD*2.*VREL
      DRSWYD=(DFYDYD-D3)*(COS(DR)*YSW-SIN(DR)*ZSW)+D3*ZS
      DRUDYD=RDC*(ENDFAC/V)*ZR
      DRYD=(DRSWYD+DRUDYD)/AIXX
*
*     ROLL MOMENTS W/R TO R
*
      DFYDR=-FM*D1*DRD*2.*VREL*XS
      DRSWR=(DFYDR+D3*XS)*(COS(DR)*YSW-SIN(DR)*ZSW)-D3*XS*ZS
      DRRUDR=RDC*(ENDFAC/V)*ZR*XR
      DRR=(DRSWR+DRRUDR)/AIXX
*
*     SWAY FORCES W/R TO YDOT
*
      AMASS=5810./G
      DYRDYD=-DRUDYD/ZR
      DYSWYD=(DFYDYD-D3)*SIN(DR)-D3
      DYYD=(DYRDYD+DYSWYD)/AMASS
*
*     SWAY FORCES W/R TO R
      DYRDR=-DRRUDR/ZR
      DYF=-V*AMASS
      DRSWR=(DFYDR+D3*XS)*SIN(DR)+D3*XS
      DYR=(DYRDR+DRSWR+DYF)/AMASS
*
*     SWAY FORCES W/R TO PHIDOT
*
      DYRDPD=-DRRUPD/ZR
      DYSWPD=(DFYDPD+D3*ZS)*SIN(DR)+D3*ZS
      DYPD=(DYRDPD+DYSWPD)/AMASS
*
*     SWAY FORCES W/R TO PHI
*
      DYPH=(DFYDPH*SIN(DR))/AMASS
```

```
*
      SW1=0.083
      SW2=0.015
      LAM=0.515
      MLAM=0.465
      AVBM=0.4
      CDF=0.0025
      N1=2.*V*A22S*L*MLAM
      N2=-PI/5.*RHO*L*V
      N3=PM*0.5*RHO*CDSW*((ALD+YSW*PHI)+(ALD-YSW*PHI))
      N4=(ALD+YSW*PHI)**2+(ALD-YSW*PHI)**2
      C1=SW1*L**3*2.
      C2=SW2*L**2
      XX=-0.5*RHO*CDF*V**2*L
*
*     YAW MOMENTS W/R TO YDOT
*
      DNRDYD=CYRDYD*XR
      DNSWYD=N1+N2*N4+N3*(C1*R+2.*C2*VREL)
      DNYD=DNRDYD+DNSWYD
*
*     YAW MOMENTS W/R TO R
*
      DNRDR=CYRDR*XR
      DNSWR=-N1*XS+N3*(C1*VL-2.*C2*VREL*XS)
      DNR=DNRDR+DNSWR
*
*     YAW MOMENTS W/R TO PHIDOT
*
      DNRDPD=CYRDPD*XR
      DNSWPD=-N1*ZS-N2*N4*ZS-2.*N3*C2*VREL*(ZS-ALD/2.)
      DNPD=DNRDPD+DNSWPD
*
*     YAW MOMENTS W/R TO PHI
*
      DNSWPH=2.*N2*(VL-ZS*PHD)*((ALD+YSW*PHI)*YSW-(ALD-YSW*PHI)*YSW)
      DNXPH=-4.*XX*YSW
      DNPH=DNSWPH+DNXPH
*
*
DERIVATIVE
*
*
      X1=INTGRL(A,X2)
      X2=INTGRL(A,XZ)
      X3=INTGRL(A,X4)
      X4=INTGRL(A,XP)
      X5=INTGRL(A,XMB)
```

```
      X6=INTGRL(A,X7)
      X7=INTGRL(A,XROLL)
      X8=INTGRL(A,X9)
      X9=INTGRL(A,XY)
      X10=INTGRL(A,X11)
      X11=INTGRL(A,XYAW)
      XMB=DMBZ*X1+DMBMB*X5
      XP=DTHZ*X1+DTHTH*X3+DTHMB*X5+DTHDTH*X4+DPPH*X6
      XZ=DZZ*X1+DZTH*X3+DZDP*X4+DZMB*X5+DZPH*X6
      XY=DYYD*X9+DYR*X11+DYPD*X7+DYPH*X6+(2.*FYP*SIN(RUDANG)+FRD)/AMASS
      RR=DRZ*X1+DRTH*X3+DRMB*X5+DRPH*X6+DRPD*X7
      XR1=(RR+DRYD*X9+DRR*X11)*AIXX-(2.*FYP*SIN(RUDANG)+FRD)*ZR
      XN=DNYD*X9+DNR*X11+DNPD*X7+DNPH*X6+(2.*FYP*SIN(RUDANG)+FRD)*XR
      XROLL=XR1/IK+XN/I
      XYAW=XN/IR+XR1/I
*
      DPB=DPBDZ*X1+DPBMB*X5
      FBB=PB1+DFB
      LD=LD1+X1*12.
      TH=TH1+X3*RADEG
      THDD=XP*RADEG
      ZDD=XZ/G
      PHDD=XROLL*RADEG
      PH=PH1+X6*RADEG
      XO=V*TIME
      X=XO*COS(X10)+X8*SIN(X10)
      Y=-XO*SIN(X10)+X8*COS(X10)
      YAWRT=X11
      YDOT=X9
*
SAMPLE
PREPAR 0.05,PH,X,Y,YAWRT,YDOT
CONTRL FINTIM=25.,DELT=0.01,DELS=0.031
PRINT  0.05,PH,X,Y,YAWRT,YDOT
GRAPH TIME,PH
PRPLOT ONLY
      CALL DRWG(1,1,TIME,PH)
      CALL DRWG(2,1,X,Y)
TERMINAL
      CALL ENDRW(NPLOT)
END
STOP
//PLOT.SYSIN DD *
PLOT IS ROLL ANGLE
XR-3 20 KNOTS SPEED RD=10                                                  05
0.0       5.0       0.0        0.15       5.0       6.0
PLOT IS Y VS. X DISPLACEMENT
XR-3 20 KNOTS SPEED RD=10
```

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Development of the five degree-of-freedom linear model for the XR-3 surface effect ship and investigation of the roll behavior of the craft in turn maneuvers.